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**International Center for Arid and Semi-Arid Land Studies,
Lubbock, Tex.**

Prepared for

Robert S. Kerr Environmental Research Lab, Ada, Okla.

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Managing Saline Water For Irrigation

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Texas Tech University
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16. ABSTRACT

An international conference was held at Texas Tech University in 1976 to assess the current state of knowledge about managing saline water for irrigation and to present new information on how to cope with salinity. Plant scientists, soil scientists, and engineers representing 20 countries participated in the sessions. Their findings are presented in this volume. The tone of the papers is one of optimism that moderately saline water can be used successfully for irrigation if what is known already and what is being learned now is used effectively. Mixed with the optimism is the realization that careless management of saline irrigation water can be disasterous to the land and, more importantly, to the people living on that land.

Papers on a variety of topics related to salinity were presented during the period 16 to 20 August in Lubbock. Upon the conclusion of that part of the conference nearly half of the participants went on field trips to experiment stations and irrigated areas to observe research studies and on-farm use of saline water for irrigation. Sites were visited in Texas, New Mexico, Arizona, and California.

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Soils	Desalination	water quality	
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Managing Saline Water for Irrigation

Proceedings of the International Conference on Managing Saline Water for Irrigation: Planning for the Future

Edited by

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Center for Arid and Semi-Arid Land Studies,
Texas Tech University

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PREFACE

Irrigation water salinity is becoming an increasingly serious problem as water of less and less desirable quality is exploited for irrigation and as greater intensity of water use leads to degradation. Deteriorating quality, combined with rapidly increasing energy costs, has caused a crisis in water use in pump-irrigated areas. Similarly, river waters have become more highly regulated, water evaporating from reservoirs concentrates the salts, and new irrigation projects aggravate the salinity problem for downstream users.

An international conference was held at Texas Tech University in 1976 to assess the current state of knowledge about managing saline water for irrigation and to present new information on how to cope with salinity. Plant scientists, soil scientists, and engineers representing 20 countries participated in the sessions. Their findings are presented in this volume. The tone of the papers is one of optimism that moderately saline water can be used successfully for irrigation if what is known already and what is being learned now is used effectively. Mixed with the optimism is the realization that careless management of saline irrigation water can be disastorous to the land and, more importantly, to the people living on that land.

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Financial support for the conference was provided by the U.S. Environmental Protection Agency, Texas Tech University, and UNESCO.

VARIOUS INDICES FOR EVALUATING THE EFFECTIVE SALINITY AND SODICITY OF IRRIGATION WATERS

J. D. Oster and J. D. Rhoades [1]

INTRODUCTION

Indices for the evaluation of water quality for irrigation have evolved from simple concepts and descriptive equations to refined, but complex, relationships requiring electronic computers to perform the calculations. Wilcox (1948) proposed a more flexible water quality evaluation scheme, but also equated effective salinity with the total amount of dissolved salt in the irrigation water. Wilcox did point out that Ca^{2+} and HCO_3^- would precipitate as calcium carbonate, or lime, in the soil as the irrigation water was concentrated during plant water uptake, but made no attempt to compensate for it in his assessment. Eaton (1950) considered that the precipitation of Ca^{2+} and Mg^{2+} as carbonates was complete when the sum of the HCO_3^- and CO_3^{2-} concentrations exceeded that of the divalent cations and proposed the concept of residual sodium carbonate, RSC, for evaluating the sodicity hazard of irrigation waters. The U.S. Salinity Laboratory Staff (1954) recommended that both RSC [2] and sodium adsorption ratio, SAR [3], be used to evaluate sodicity hazard. They recognized that precipitation of Ca^{2+} would not be complete, but insofar as it increased the relative Na^+ concentration of the soil solution, it was a factor to be considered.

Doneen (1954) extended the correction for precipitation to the evaluation of the salinity hazard of an irrigation water. He proposed a term "effective salinity," expressed in meq/liter, which was calculated by subtracting $Ca(HCO_3)_2$, $Mg(HCO_3)_2$ and $CaSO_4$, in that order, from the total concentration. The remaining salts, being more soluble, were assumed to be the only ones effective in salinizing the soil solution. In fact, precipitation is not complete; its extent depends upon leaching fraction, (LF), composition of irrigation water, and partial pressure of CO_2, (P_{CO_2}), (Rhoades, 1974, and Oster and Rhoades, 1975).

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[1] U.S. Salinity Laboratory, Riverside, California.

[2] RSC = $C_{CO_3} + C_{HCO_3} - C_{Ca} - C_{Mg}$ where all concentrations, C, are expressed in meq/liter.

[3] SAR = $C_{Na}/[(C_{Ca} + C_{Mg})/2]^{\frac{1}{2}}$.

Bower (1961) introduced the use of the term pH_c^* [4] to account for lime precipitation. The concept is based on lime-pH equilibria. pH_c^* is the calculated pH that water should have when in equilibrium with lime at atmospheric P_{CO_2}. Bower et al. (1968) showed that the amount of carbonate precipitation which occurred in lysimeter studies was related to pH_c^* and LF. The measured SAR of the drainage water was highly correlated with the SAR calculated according to the equation,

$$SAR_{dw} = \frac{SAR_{iw}}{\sqrt{LF}} \left[1 + (8.4 - pH_c^*)\right], \qquad (1)$$

where the subscripts dw and iw represent drainage and irrigation water.

Current water quality guidelines include modified versions of Equation 1 (Rhoades, 1972, and Ayers and Branson, 1975) for estimating the sodicity hazard of irrigation waters. The assessment is based on two equations: 1) The SAR for the surface soil, SAR_{su} is calculated according to,

$$SAR_{su} = SAR_{iw} \left[1 + (8.4 - pH_c^*)\right]; \qquad (2)$$

and 2) The SAR for the soil at the lower boundary of the root zone, SAR_l, is calculated according to,

$$SAR_l = \frac{(y^{1+2LF})}{\sqrt{LF}} (SAR_{iw}) \left[1 + (8.4 - pH_c^*)\right], \qquad (3)$$

where y is an empirical mineral-weathering parameter proposed by Rhoades (1968).

Several simple methods that do not account for precipitation are available to evaluate the salinity hazard of an irrigation water. Bernstein and Francois (1973) proposed that crop response should be related to the water-uptake-weighted mean salinity. This mean salinity, $\overline{C}$, is related to LF according to the equation

$$\overline{C} = \left[C_{iw}/(1-LF)\right] \ln(1/LF), \qquad (4)$$

where C is concentration expressed in meq/liter. Ingvalson et al., (1976) and Rhoades and Merrill (1975) concluded that plant response correlated better with the average root zone salinity. This average, expressed in terms of the EC of the saturation extract, $\overline{EC}_e$, was related to leaching fraction and EC_{iw} according to the equation

---

[4] $pH_c^* = (pk_2 - pk_c) + p(Ca + Mg) + p(Alk)$ where p(Ca + Mg) and p(Alk) are negative logarithms of the molar concentrations of Ca + Mg and of the equivalent concentration of titratable base ($CO_3 + HCO_3$), respectively, and pk_2 and pk_c are the negative logarithms of the second dissociation constant of H_2CO_3 and of the solubility constant of $CaCO_3$, respectively, both corrected for ionic strength (Bower and Maasland, 1963).

$$\overline{EC}_e = 0.2\ EC_{iw} \left[1 + 1/LF\right] \qquad (5)$$

(Rhoades and Merrill, 1975). Rhoades (1974) described the underlying assumptions used to obtain Equation 5 and its application in terms of existing salt tolerance data. All of the above equations are simple to use and their predictive capabilities are fairly well substantiated.

Equations 2-5 may not apply equally well for all types of waters. Precipitation of lime from a water is dependent upon P_{CO_2}, and the concentrations of other dissolved ions. The same would be true for the precipitation of magnesium carbonate, or magnesite. However, this mineral is rarely observed in nature (Strum and Morgan, 1970), and probably does not precipitate in soils. For water high in SO_4^{2-}, gypsum, ($CaSO_4.2H_2O$), precipitation can also occur. Because of these and other complex interactions, computer simulation modeling based on the physical chemistry of gypsum solubility in mixed salt solutions, begun by Dutt and Tanji (1962) and Dutt and Doneen (1963), provides a potential alternative method for water quality assessment. Building on this work Oster and Rhoades (1975) modified the model to include lime solubility and concluded that simulation modeling was a valid method for evaluating salinity, sodicity,and pollution hazards of irrigation waters. Rhoades and Merrill (1975) used this predictive chemistry model to assess the effect of irrigation managment on irrigation water quality.

In this paper we compare the results obtained with computer simulation methods based on the physical chemistry of mixed salt solutions with those obtained by the simple equations to evaluate their relative suitability to assess irrigation water quality.

METHODS

Data on the irrigation waters selected for this work were obtained from our files. These waters represent a worldwide selection of river and groundwaters with EC's greater than 0.2 mmho/cm and for which the chemical analysis indicated the sum of cations and anions was approximately the same. Some general properties of the selected waters are presented in Table 1. A wide range of concentration and composition is represented, although more than half of the waters had an EC of less than 1.5 mmho/cm and half had SAR's of less than 3. Almost all the waters were lime saturated; i.e., only a few had pH_c^* values exceeding 8.0. Water composition is believed to vary enough to enable evaluation of the different methods of assessing salinity and sodicity hazards of irrigation waters.

Soil water compositions were calculated using a Fortran simulation program that accounts for the effects of ionic strength and ion pair

Table 1. Properties of selected irrigation waters.

EC (mmho/cm)	No. of Water Samples	SAR $(meq/1)^{1/2}$	No. of Water Samples	pH_c^*	No. of Water Samples	Predominant Anions	No. of Water Samples
.2-.5	23	<1	16	<6.5	2	$>1/2\ HCO_3$	35
.5-1.	23	1-3	38	6.5-6.9	9	$>1/2(HCO_3+SO_4)$	72
1.0-1.5	17	3-5	13	6.9-7.3	36	$>1/2\ SO_4$	22
1.5-2.0	9	5-7	12	7.3-7.7	35	$>1/2(SO_4+C1)$	67
2.0-2.5	8	7.10	12	7.7-8.0	15	$>1/2\ C_1$	30
2.5-3.0	4	>10	11	>8.0	5		
3.0	16		-				
	102		102		102		

equilibria on lime and gypsum solubilities (Oster and Rhoades, 1975) 5/. Based on analytical verifications of the calculated soil water compositions, we consider the simulation program a valid reference for comparing the simpler methods.

Equilibrium concentrations of soil solution through the root zone, for leaching fractions of 0.1 and 0.4, and for specified P_{CO_2}, were calculated from the composition of the irrigation water by assuming soil solution was saturated with respect to lime with a solubility product of 6.46×10^{-9}. The soil solution composition was calculated for five soil depths - the soil surface, and 1/4, 1/2, 3/4 and full depths of the root zone. The following assumptions were considered reasonable for many crops (Rhoades, 1975). The relative water uptake for the four successive soil intervals from the surface downward was 40, 30, 20 and 10% of the total, respectively. The P_{CO_2} was .0007 atm at the soil surface and .005, .015, .023 and .030 atm for each successive soil interval downward. The soil water composition, sum of cations, SAR and EC (McNeal et al., 1970) were calculated for each depth. Other parameters calculated were average profile EC, water-uptake-weighted salinity, and SAR at the soil surface and at the bottom of the root zone.

Average and water-uptake-weighted salinities were also calculated assuming negligible precipitation. Equation 4 was used to calculate water-uptake-weighted salinity of each water at LF's of 0.1 and 0.4. The average root zone salinity, $\overline{EC}$, was calculated from the water uptake distribution according to

$$\overline{EC} = \frac{EC_{iw}}{5}\left[1 + \frac{1}{.64} + \frac{1}{.37} + \frac{1}{.19} + \frac{1}{.10}\right] = EC_{iw} * 4.11 \quad (6)$$

for LF = 0.1 and

$$\overline{EC} = \frac{EC_{iw}}{5}\left[1 + \frac{1}{.76} + \frac{1}{.58} + \frac{1}{.46} + \frac{1}{.40}\right] = EC_{iw} * 1.74 \quad (7)$$

for LF = 0.4.

These equations represent the average of the sum of the calculated EC values at the boundaries of a root zone that was segmented into four soil layers. $\overline{EC}_e$ was also calculated according to Equation 5. The $\overline{EC}_e$ of the soil solution in the root zone was estimated by multiplying $\overline{EC}_e$ by 2.

5/ Documented program available upon request.

RESULTS AND DISCUSSION

Calcium Precipitation

The predicted amounts of Ca^{2+} precipitated or dissolved as calculated by the simulation model were related to the RSC and pH_c^* values of the waters by standard correlation analysis. The **amount of Ca^{2+} precipitated** at a given LF was expressed as a fraction of the Ca^{2+} in the irrigation water. If the irrigation water dissolved lime, the percentage was negative.

A comparison between relative Ca^{2+} precipitation for a LF of 0.1 was compared with RSC for 59 waters containing more HCO_3^- than Ca^{2+}. Waters for which gypsum precipitation was predicted were excluded. As shown in Figure 1, precipitation and RSC are not correlated. The figure clearly demonstrates that over half of the Ca^{2+} is predicted to precipitate in the majority of the cases even when RSC has a negative value. In contrast, a definite correlation exists between the relative Ca^{2+} precipitation and pH_c^* for the same set of waters (Fig. 2). The correlation coefficient for the second-degree equation was 0.82. The data for 43 waters where HCO_3^- was less than Ca^{2+} can be seen in Figure 3. The correlation coefficient for the regression line shown is 0.43, significantly lower than for the previous case. Gypsum precipitation in 23 of these waters partially accounts for the lower correlation. However, the extent of precipitation is noteworthy, exceeding 30 percent in all but two cases.

At a LF of 0.4, Ca^{2+} can either precipitate (+) or dissolve (-) (Fig. 4). With all the waters included, the correlation coefficient was 0.78 for the second-degree regression line shown. Grouping the waters in the same categories as was done for LF of 0.1, the correlation coefficients were 0.80 for the waters in which HCO_3^- exceeded Ca^{2+} and 0.69 for those in which it didn't. The latter correlation coefficient is considerably better than the 0.43 obtained for the same group of waters at a LF of 0.1. That pH_c^* is correlated with both a gain or loss of Ca^{2+} is one of its chief attributes.

The effects of gypsum on relative Ca^{2+} precipitation at a LF of 0.1 were correlated with the product ($C_{Ca}*C_{SO_4}$), where C represents the concentration, in meq/liter, of the ion in the irrigation water. For example, a water that contains 5 meq/liter of Ca^{2+} and 6 meq/liter of SO_4^{2-} has a product of 30 $(meq/l)^2$. If one assumes no precipitation, the predicted concentrations at a LF of 0.1 are tenfold greater and the concentration product would be 3000 $(meq/l)^2$. For comparison, the product of a saturated gypsum solution made from distilled water would have a value of about 900 $(meq/l)^2$. The solubility of gypsum is increased by SO_4^{2-} ion pair formation with Na^+ and Mg^{2+}, and by ionic strength. Therefore, saturated gypsum soil solutions have products in excess of 900 $(meq/l)^2$. At LF of 0.1, gypsum did precipitate in some instances when the value of $C_{Ca}*C_{SO_4}$ in the water slightly exceeded 30 $(meq/l)^2$. Thirty waters had a

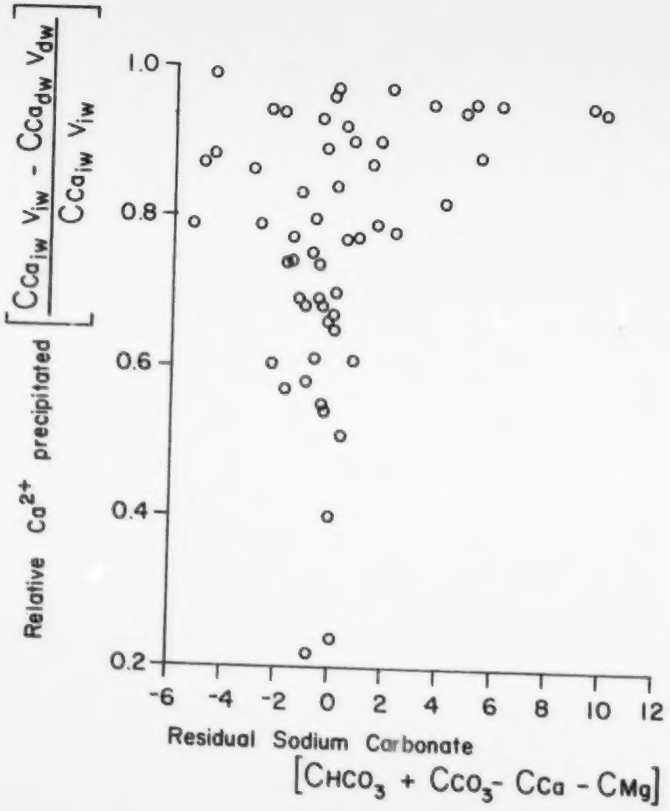

Figure 1: Relative Ca^{2+} precipitated at a LF of 0.1 for waters which contained more HCO_3^- than Ca^{2+} as a function of residual sodium carbonate of the irrigation water.

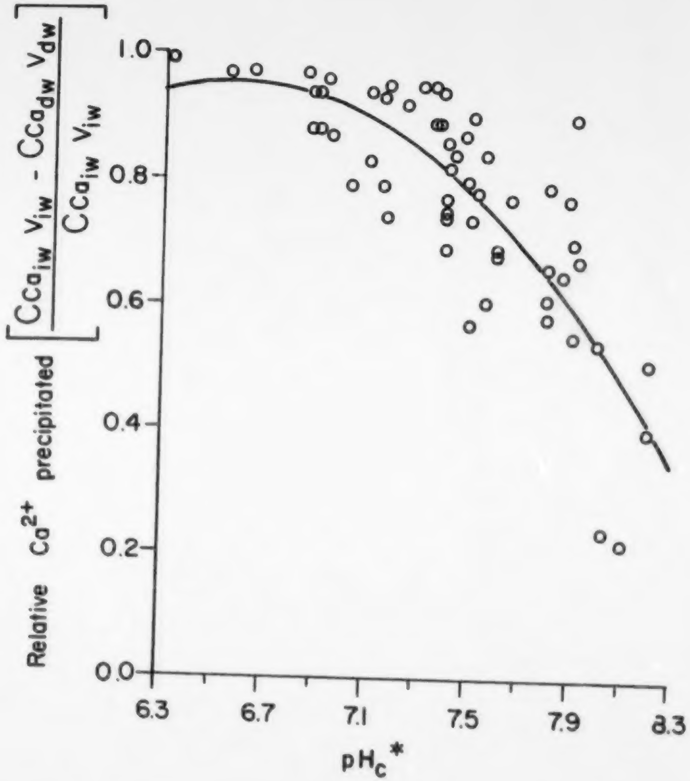

Figure 2: Relative Ca^{2+} precipitated at a LF of 0.1 for waters which contained more HCO_3^- than Ca^{2+} as a function of the pH_c^* of the irrigation water.

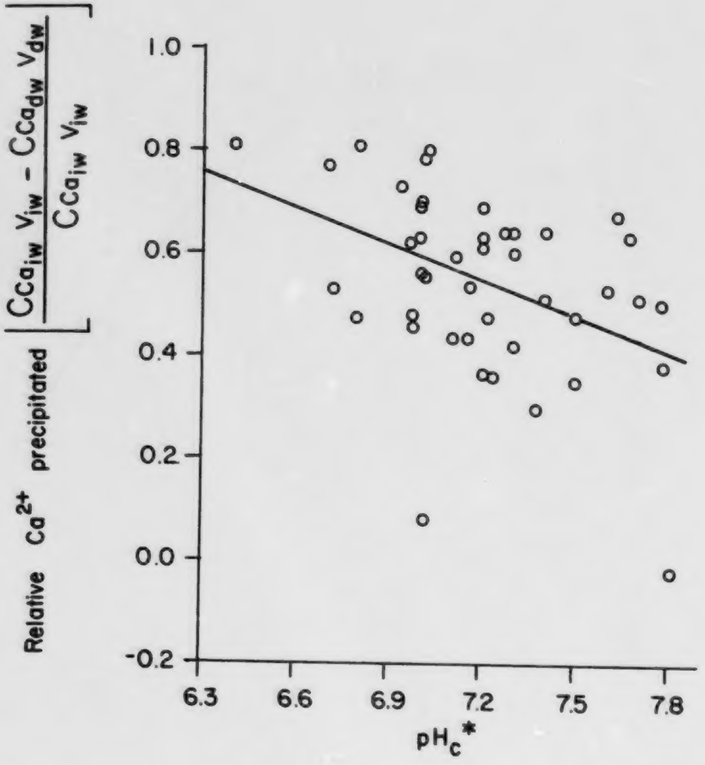

Figure 3: Relative Ca^{2+} precipitated at a LF of 0.1 for waters which contained more Ca^{2+} than HCO_3^- as a function of the pH_c^* of the irrigation water.

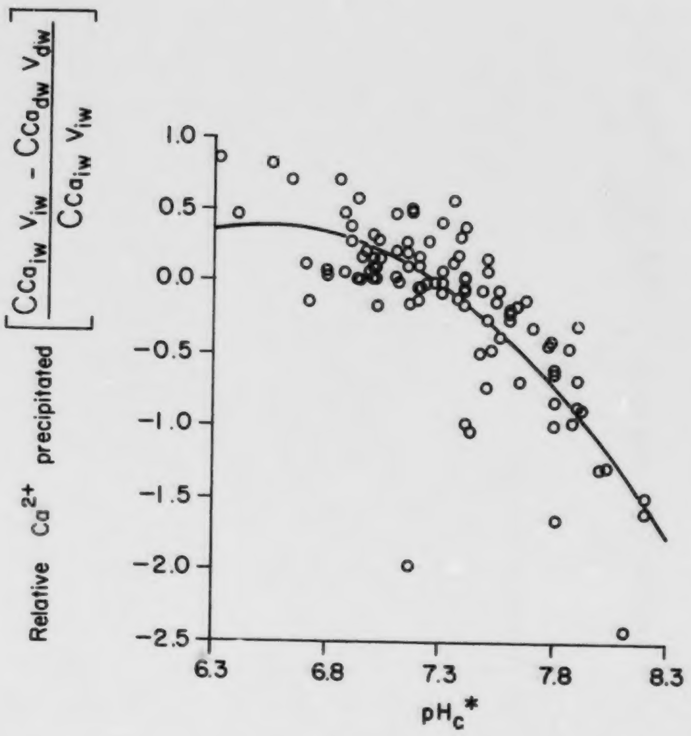

Figure 4: Relative Ca^{2+} precipitated at a LF of 0.4 as a function of pH_c^*.

product exceeding 30 and of these, only one contained more HCO_3^- than Ca^{2+}. By eliminating this water, the second degree regression line relating relative calcium precipitation to (C_{Ca}*C_{SO_4}) (where the product exceeded 30) had a correlation coefficient of 0.8. The equation was

$$\text{Rel. Ca precip.} = -.0001\,(C_{Ca} * C_{SO_4})^2 + .13\,(C_{Ca} * C_{SO_4}) + 44.3$$

When the concentration product exceeds 100, more than 50% of the calcium is predicted to precipitate. The amount of precipitation increased to 75% at values of (C_{Ca} * C_{SO_4}) $\sim$ 300, and levels off at 80% at 550.

Salinity Parameters

The results of the correlation analysis for the various salinity parameters are given in Table 2. The average salinity values calculated by Equations 6 and 7 for a LF of 0.1 are by 15 to 20% greater than the precipitation-corrected values. As expected, the difference is greatest for waters where the product, (C_{Ca} * C_{SO_4}), exceeds 30. In other words, the sum of gypsum and lime precipitation is greater than precipitation of lime alone. Equation 5, which was based, in part, on observed salinity profiles in lysimeters, produced estimated average salinities that are about 32% more than the corrected values. On the other hand, because water-uptake-weighted salinity gives greater weight to salinity at shallow depths, precipitation correction for gypsiferous waters in terms of water-uptake-weighted salinity is quite small. The same is true for average salinity at a leaching fraction of 0.4. The correction for precipitation reduces the calculated average EC only 5%.

Sodicity Parameters

Figure 5 shows the regression relationships obtained between SAR calculated according to Equation 2 and 3 and that calculated by the simulation model. The surface SAR, calculated according to Equation 2, is about 2 times greater than that corrected for precipitation. The regression equation is y = 2.1 x -.19 with a correlation coefficient of 0.98, where y is the predicted SAR calculated from Equation 2 or 3 and x is that calculated from the simulation model. The high values stem from several causes: 1) pH_c^* is calculated from the sum of Ca^{2+} and Mg^{2+} which overcorrects for calcium precipitation; 2) SAR_{su} calculated according to Equation 2 assumes the pH of a saturated lime solution to be 8.4, whereas the pH of a saturated lime solution under the conditions assumed in the simulation model, would be 8.16; and 3) the pH_c^* concept may underpredict the solubility of lime. The regression equation, where only Ca^{2+} concentration is used to calculate pH_c^*, is y = 1.82 x -.19. Elimination of Mg^{2+} does not reduce the slope to a value of 1.0. Nor does the combination of eliminating Mg^{2+} and changing 8.4 to 8.16 in Equation 2. The resulting regression equation is y = 1.61 x -.23. Apparently the pH_c^* concept does underpredict the solubility of lime, and the error increases with increasing SAR.

Table 2. Regression equations and correlation coefficients for average root zone salinity

Parameter	Condition	Equation[1]	Coefficient	No. of Water Samples
	LF = .1			
average salinity (a) equation (6)	$(C_{Ca}*C_{SO_4})<30$	1.15 x +.39	.993	49
	$(C_{Ca}*C_{SO_4})>30$	1.21 x +.90	.986	30
(b) equation (5)	None	1.32 x +.32	.990	77
Water-uptake-weighted equation (4)	$(C_{Ca}*C_{SO_4})>30$	1.03 x +4.5	.996	30
	LF = .4			
average salinity equation (7)	$(C_{Ca}*C_{SO_4})<30$	1.05 x +.05	.991	49
	$(C_{Ca}*C_{SO_4})>30$	1.05 x +.19	.990	30

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[1] equation refers to the linear regression relationship between the predicted parameter, y, as calculated by the indicated equation, and that calculated by the simulation model, x.

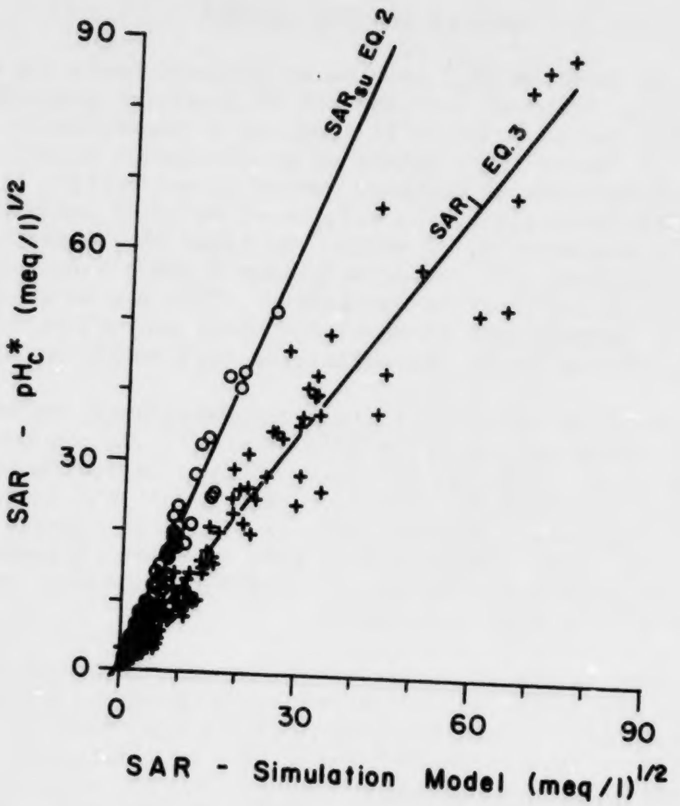

Figure 5. Calculated SAR on the basis of pH_c^* as a function of that calculated by simulation model.

The SAR of the drainage water calculated from Equation 3 and that from the simulation model closely agree for both a LF of 0.1 and 0.4. The regression equation is $y = 1.14x - .16$ and the correlation coefficient is .98. The agreement and high correlation is not surprising, since the mineral weathering coefficient is an empirical constant chosen so that observed and predicted SAR's of drainage waters are equal. As such it includes effects of increased P_{CO_2}'s in the soil atmosphere, increased lime solubility, as well as any hydrolysis of exchangeable cations or silicate weathering.

SUMMARY AND CONCLUSIONS

Simplified models based on pH_c^* provide an adequate basis for assessing water quality. Although the accuracy of predicted precipitation for low LF's based on pH_c^* may be limited, it is sufficient to permit the assessment of the sodicity hazard of an irrigation water. The accuracy of predicted SAR of drainage waters is well within the current status of knowledge of the effects of salinity and sodicity on the hydraulic conductivity of soils. In terms of the predicted SAR of the soil surface, the use of equations 2 and 3 based on pH_c^* will tend to give a conservative assessment. This may be what is needed, since one of the largest gaps in knowledge about the effect of SAR on hydraulic conductivity is for low salinities (concentrations < 10 meq/l).

We believe corrections for precipitation are unwarranted to assess salinity hazards of irrigation water for LF's of ≥ 0.1. On the basis of water-uptake-weighted salinity, the correction is insignificant. The 15 to 20% reduction in average root zone salinity is not large, particularly when one considers that most irrigated projects operate at LF's greater than 0.1. Also, salt tolerance data in terms of average root zone salinity obtained under one set of conditions and applied under another are subject to some uncertainty.

Complex simulation models will continue to be used to assess water suitability for irrigation at our laboratory because one always prefers to make such judgements using the most accurate and practical tools available. Using a direct terminal connection to a computer, we simply input the water composition of concern and all calculations and tabulations are made and conveniently printed for mailing. The simpler methods could also be programmed, but the computer model has additional benefits. Ionic composition is given so specific ion toxicities can be assessed. Ion ratios, Ca^{2+}/Mg^{2+} and SAR, and pH distribution throughout the root zone aid in the evaluation of potential nutritional imbalance and availability problems. In addition, benefits of chemical amendments and effects of different CO_2 levels or water uptake patterns can be evaluated. The distribution of lime and gypsum precipitation is also tabulated and can be used to evaluate potential problems arising from changes in soil porosity.

LITERATURE CITED

Ayers, Robert S., and Roy L. Branson. 1975. Guidelines for Interpretation of Water quality for Agriculture. University of California Extension, Memo., 13 pp.

Bernstein, Leon and L. E. Francois. 1973. Leaching requirement studies: Sensitivity of alfalfa to salinity of irrigation and drainage waters. Soil Sci. Soc. Amer. Proc. 37:931-943.

Bower, C. A. 1961. Prediction of the effects of irrigation waters on soils. In Salinity Problems in the Arid Zones. Proc. UNESCO Arid Zone Symp. (Tehran, Iran) 14:215-222.

Bower, C. A. and M. Maasland. 1963. Sodium hazard of Punjab groundwaters. In Symposium on Waterlogging and Salinity in West Pakistan. West Pakistan Eng. Congr. 50:49-61.

Bower, C. A., G. Ogata, and J. M. Tucker. 1968. Sodium hazard of irrigation waters as influenced by leaching fraction and by precipitation or solution of calcium carbonate. Soil Sci. 106:29-34.

Doneen, L. D. 1954. Salination of soil by salts in irrigation water. Trans. Am. Geophys. Union: 35, 60, 943-950.

Dutt, G. R. and K. K. Tanji. 1962. Predicting concentrations of solutes in water percolating through a soil. J. Geophys. Res. 67:3437-3439.

Dutt, G. R. and L. D. Doneen. 1963. Predicting the solute composition of the saturation extract from soil undergoing salinization. Proc. Am. Soil Sci. Soc. 27: 627-630.

Eaton, Frank M. 1950. Significance of carbonates in irrigation waters. Soil Sci. 69:123-133.

Ingvalson, R. D., J. D. Rhoades, and A. L. Page. 1976. Correlation of alfalfa yield with various indices of salinity. Soil Sci. (In press).

McNeal, B. L., J. D. Oster, and J. T. Hatcher. 1970. Calculation of electrical conductivity from solution composition data as an aid to in-situ estimation of soil salinity. Soil Sci. 110:405-414.

Oster, J. D., and J. D. Rhoades. 1975. Calculated drainage water compositions and salt burdens resulting from irrigation with river waters in the western United States. J. Environ. Qual. 4:73-79.

Rhoades, J. D. 1968. Mineral-weathering correction for estimating the sodium hazard of irrigation waters. Soil Sci. Soc. Amer. Proc. 32:648-652.

Rhoades, J. D. 1972. Quality of water for irrigation. Soil Sci. 113:277-284.

Rhoades, J. D. 1974. Drainage for salinity control. In: Jan van Schilfgaarde (ed.), Drainage for Agriculture. Agronomy 17, pp. 433-461.

Rhoades, J. D. 1975. Water Quality Assessment Model. Annual Report. U.S. Salinity Laboratory Location Office, 4500 Glenwood Drive, Riverside, California. 151-153 pp.

Rhoades, J. D. and S. D. Merrill. 1975. Assessing the suitability of water for irrigation: Theoretical and empirical approaches. Proc., Expert Consultation on Prognosis of Salinity and Alkalinity, Rome, Italy, June 1975. (In press).

Strum, W. and J. L. Morgan. 1970. Aquatic Chemistry. Wiley Interscience, New York, 583 pp.

United States Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S. Dept. Agr. Handbook 60. 160 pp.

Wilcox, L. V. 1948. The quality of water for irrigation. U.S. Dept. Agri. Tech. Bull. 962, 1-40.

IRRIGATION MANAGEMENT WHERE SALINITY SOURCES AND SINKS ARE PRESENT

R.J. Hanks, L.S. Willardson, J.J. Jurinak and J.D. Melamed 1/

INTRODUCTION

Accurate prediction of the effect of irrigation management on the salinity of the root zone and on the quality of drainage water must be made if future irrigation is to be successful over a long time. Many successful operating irrigation systems, using design criteria that ignored the amount of salt and drainage water, are being made subject to restrictions that may require new management practices. Many mathematical models have been developed to make predictions of irrigation management effects on soil and drainage water salinity. Most models require the soil to be inert with no precipitation or dissolution of salts (Bresler and Hanks, 1969; **Warrick et al., 1971; Bresler, 1973; Smajstrala et al., 1975; Childs and Hanks,** 1975.

However, most field situations are characterized by soils that are not inert. Many soils and associated irrigation water systems have been found to exhibit source-sink processes. The source-sink processes involve many complex chemical reactions such as exchange, precipitation, solution, etc. These processes are especially important in soils with predominantly calcium and magnesium sulfate systems. Some authors using chemical models that account for source-sink processes have obtained good predictions of soil profile salinity for some laboratory and field situations (Tanji et al., 1972; Dutt et al., 1972a, **Oster and Rhoades, 1975**).

The authors and their associates have found soil conditions in the Ashley Valley near Vernal, Utah, that exhibit strong source-sink tendencies (King and Hanks, 1975; Bliesner et al., 1976). Attempts by Gupta (1972) to incorporate the complex chemical models (Dutt et al., 1972) into the water flow model of Nimah and Hanks (1973) to simulate field conditions over a season, were not successful. This failure was attributed to lack of pertinent data associated with chemical reaction coefficients where water content changed with time and depth and where root extraction was of major importance. In field experiments it was found impossible to change the soil solution salinity to any extent below 30 cm with a wide variety of field treatments (King and Hanks, 1975; Bliesner et al., 1976). These two problems indicated that it might

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be possible to develop an emperical model that would allow predictions of source-sink responses in soils without knowing all of the complex processes involved. Consequently, the model reported here was developed.

MODEL DEVELOPMENT

One requirement in the development of this model was that it would require only easily measured soil properties. Consequently, it deals with salts in terms of total salinity as measured by electrical conductivity rather than in terms of individual salt species. The model was developed by modifying the salt flow portion of the Childs and Hanks (1975) model. This model has the advantage that the yield estimates are produced as influenced by irrigation management.

For determining the source-sink term, the following assumptions were made:

1. The most important source-sink processes are dissolution and precipitation.
2. The ion exchange process is of minor importance because the model treats the salt movement in terms of total salinity and the ion exchange capacity is relatively unaffected by the salinity levels encountered in this study.
3. Chemical changes due to biological activities are quantitatively small and considered negligible. This would not be true if nitrates were significant.
4. There is a soil solution concentration (R) at which there is no precipitation and no dissolution. If the concentration of the soil solution (C) is greater than R, precipitation will occur. If R is greater than the concentration of the soil solution, dissolution will occur (if soluble salt in solid state exists).
5. The rate of the process, whether precipitation or dissolution, is considered constant.

As a result of the above assumptions, the source-sink term was assumed to be:

$$\begin{aligned} &S = \alpha K(R - C) \\ &\text{where } \alpha = 1 \quad S > 0 \\ &\qquad\quad\ \alpha = 0 \quad S = 0 \end{aligned} \tag{1}$$

where K is a coefficient of proportion related to the soil properties and salt composition and S is concentration of solid salts. Adding this term to the general salt flow equation of Warrick et al. (1971) gives:

$$\frac{\partial(C\theta)}{\partial t} = \frac{\partial}{\partial z} D(\theta,q) \frac{\partial(qC)}{\partial z} + \alpha K(R - C) \tag{2}$$

where θ is the volumetric water fraction, C is concentration of the solution, $D(\theta,q)$ is apparent diffusion coefficient (the sum of the molecular diffusion and the hydrodynamic dispersion), and q is the water flux.

Note that when R < C the source-sink term is negative, indicating precipitation. When R > C, the source-sink term is positive, indicating dissolution.

Input Data Requirements. The data input requirements for the model are given in detail in Nimah and Hanks (1973), Childs and Hanks (1975) and Melamed et al. (1976). They can be summarized as follows:

1. Soil properties. These include hydraulic conductivity-θ and matric suction-θ relations (Nimah and Hanks, 1973). Data of initial water content and solution concentration profiles at the beginning of the simulation are needed. In addition, data for diffusion and dispersion coefficients as well as values for R and K are needed (Childs and Hanks, 1975; Melamed et al., 1976).
2. Plant properties. These include root depth-time relations. Plant cover vs. time information is also needed to determine potential transpiration and evaporation as a function of time (Nimah and Hanks, 1973; Childs and Hanks, 1975).
3. Climatic factors. These are included in potential evapotranspiration as a function of time. Rainfall amounts and timing information are also needed (Nimah and Hanks, 1973).
4. Irrigation Factors. These include irrigation amounts, time, and electrical conductivity of the irrigation water.

Model Limitations. The model is limited because it treats one-dimensional flow only. Soil properties are well known to have large spatial variability. Irrigation application is also variable. The model is a one-dimensional model, but Childs and Hanks (1975) have used it to evaluate irrigation uniformity effects. Consequently, it is advisable to run a field calibration trial to adjust for soil properties to produce results that agree with the average soil conditions.

Another serious limitation is the evaluation of the equilibrium concentration, R, in the field. Melamed et al. (1976) found that this value was not constant at any one location for Ashley Valley, Utah, but varied with depth. Bliesner et al. (1976) found that the R value varied spatially and also that rather drastic leaching variations did not change this value significantly in one year. Thus, the value of R must be determined for the soil in place. The value found for R, however, is meaningful only so long as there is an excess of solid salt in the profile to govern equilibrium or steady state concentration in the soil solution. Once the solid salts have been dissolved (or weathered) there is no reason to expect the same value of R would prevail during subsequent precipitation. This points to a need for understanding of the chemical processes involved and illustrates a disadvantage of the empirical approach.

To further illustrate the situation in Ashley Valley, Table 1 shows a typical analysis of the irrigation water and a soil profile at the site.

The data show that the principle cations are calcium and magnesium and the anions are sulfates.

To further illustrate the strong source-sink effect the data of Figures 1 and 2 are shown which were taken from Bliesner et al. (1976). Figure 1 shows the expected (assuming an inert soil) and measured average electrical conductivities as a function of time for three leaching amounts. The measured data show no change in electrical conductivity where a very large change would be expected for an inert soil.

Figure 2 shows the electrical conductivity profile at three different times during the season where there was essentially no leaching. The measured data indicate no change in solution concentration, where a large change would be expected for an inert soil. Note there is a variation with depth but not time.

Table 1. Analysis of the irrigation water and a typical soil profile at Ashley Valley, Utah.

	Cations		meq/l		Anions	
	Ca	Mg	Na	Cl	SO_4	EC_e
Irrigation water	9.2	8.9	0.9	0.3	15.0	
Soil 0- 30 cm	9.4	5.7	2.1	0.8	11.8	1.5
Soil 30- 60 cm	24.7	18.4	3.9	0.8	48.2	3.2
Soil 60- 90 cm	24.0	36.0	5.7	1.8	64.4	4.0
Soil 90-120 cm	20.0	53.5	9.1	1.7	94.6	5.5
Soil 120-150 cm	19.8	45.3	15.6	1.9	94.1	5.5
Soil 150-180 cm	25.7	20.6	4.1	1.4	41.0	3.5

MODEL PREDICTIONS

Model predictions for several management situations were made using field data from the Ashley Valley, Utah, Farm. The soils data were the same as those used by Childs and Hanks (1975) except for the initial water content-salt concentration profiles. The crop was taken to be alfalfa with a rooting depth pattern to a depth of 116 cm that did not change with time, the same as used by Childs and Hanks (1975). A typical growing season was taken as 125 days and was assumed the same for all years. Irrigation was applied at 15 day intervals with approximately constant amounts. Potential evapotranspiration was varied in a normal way during the season but amounted to 81.5 cm, of which 72.7 cm was potential transpiration and 8.8 cm was potential evaporation.

Figures 3 and 4 show the profiles of salt concentrations in the solution and solid salt concentrations for a series of model simulation runs

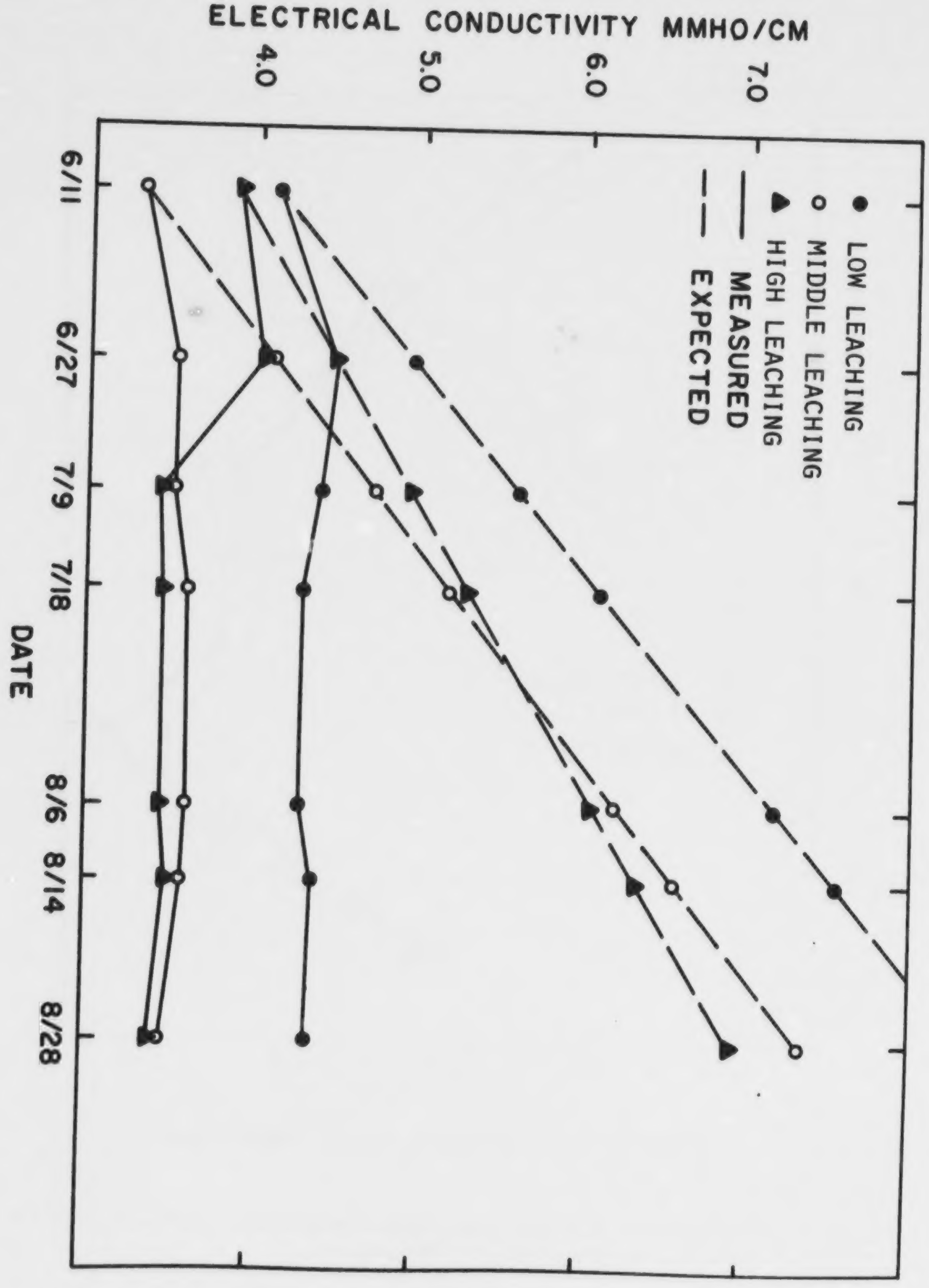

Figure 1: Measured and expected (assuming no source-sink) average soil water solution electrical conductivity with time for three leaching treatments.

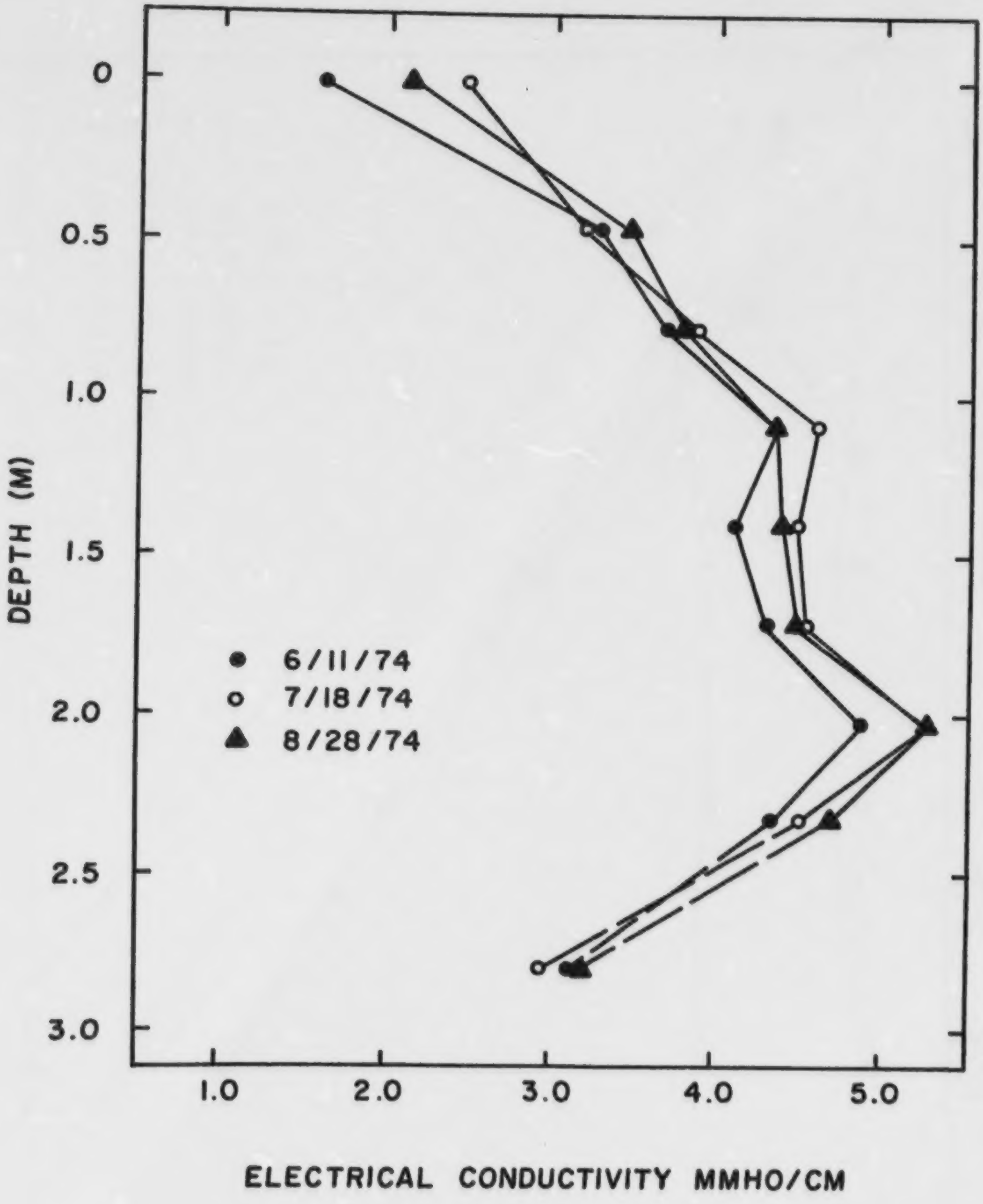

Figure 2: Average soil solution electrical conductivity profile for low leaching plots on three dates.

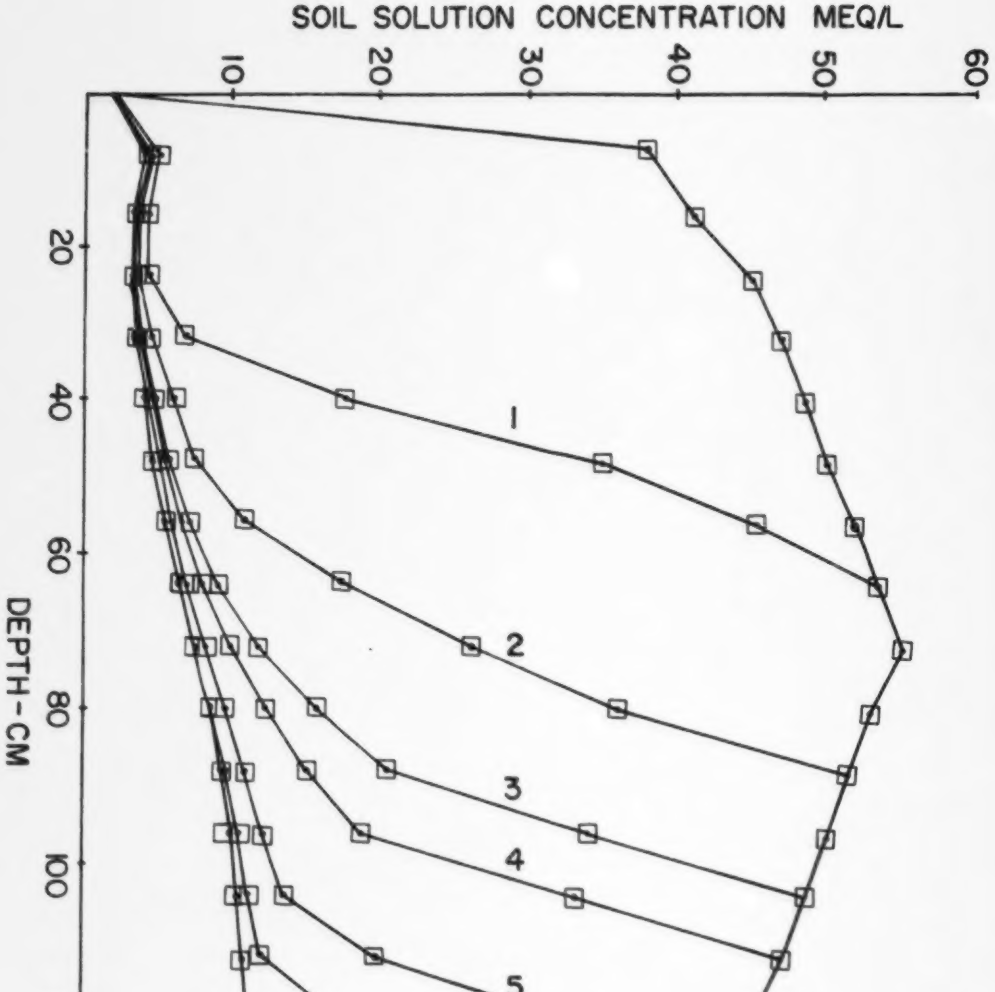

Figure 3: Salt concentration in solution phase as a function of depth and time. Irrigation was 106 cm/yr with good water quality (2 meq/l).

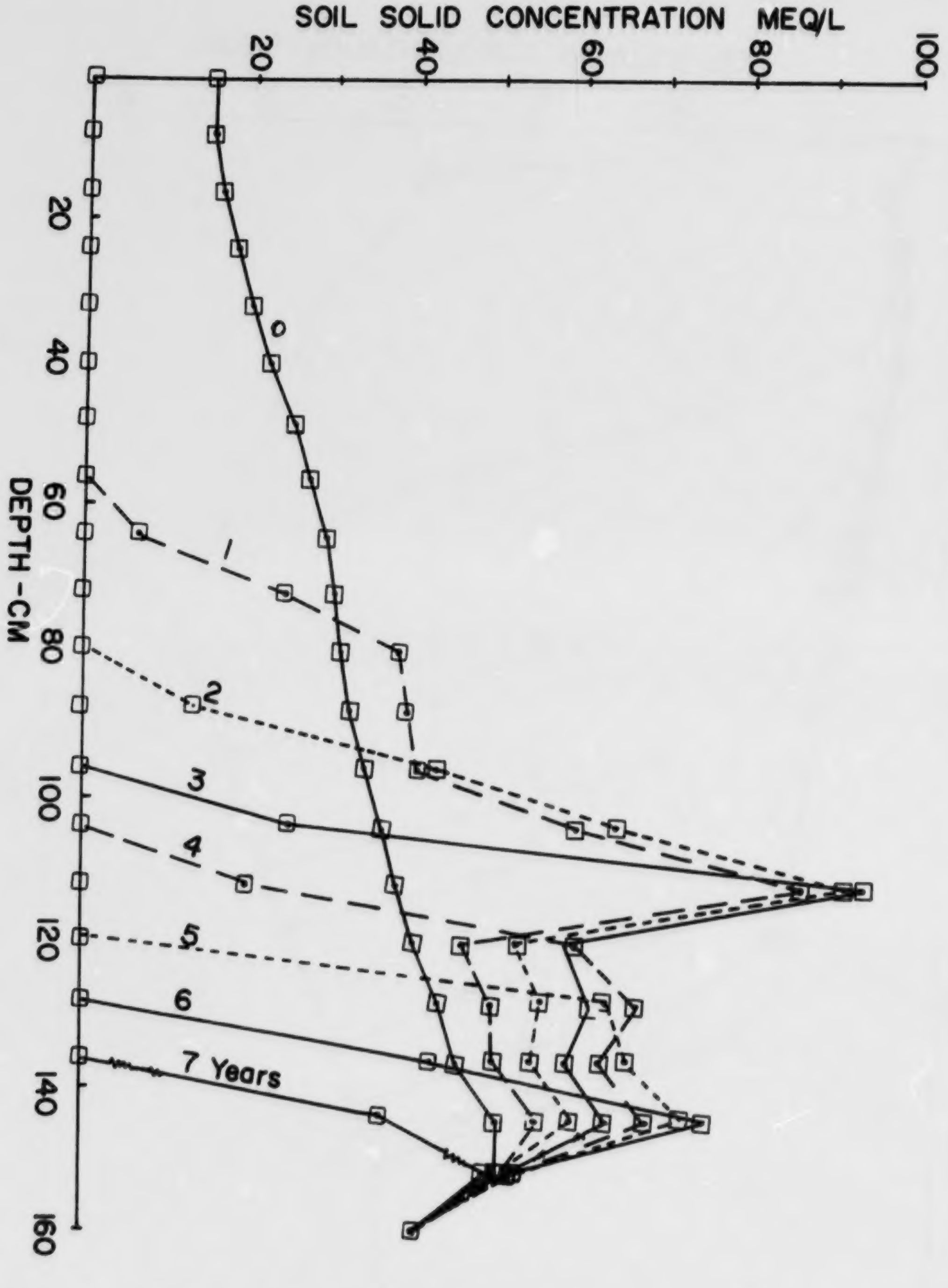

Figure 4: Salt concentration in solid phase as a function of depth and time. Irrigation was 106 cm/yr with good water quality (2 meq/l).

totaling 7 years. The total irrigation applied was 106 cm each year with a concentration of 2 meq/l in the irrigation water. With this situation there was 25 cm of water leached out of the profile. There was a water table at 160 cm. The value of R was considered variable with depth and was taken to be the same as the initial solution concentration shown in Figure 3. The amount of solid salt present at the beginning of the first year was estimated from the difference between the electrical conductivity of the saturation extract and 1:5 extract as given by Melamed et al. (1976).

The predictions of this model show (Figure 3) that it took 7 years to leach the stored salts out of the soil profile. The amount of salt going into the drainage water was simply the product of the salt concentration just above the water table and the total water drained out. The model predicted precipitation of salts near the bottom of the profile (where the solid salt concentration increased) and solution of solid salts (where the concentration decreased) in the upper part of the profile. There was a net equal removal of salt from the profile every year.

These data indicate that a long time is needed to cause any significant changes in the soil profile salt situation. The predictions agree with the measurements of Bliesner et al. (1976) that considerable variation in leaching fractions and irrigation water quality over a single growing season had very little effect on the soil solution concentration. This was borne out by preliminary computations made with a leaching fraction of near zero which predicted essentially no change in solution concentrations over several years.

Figures 5 and 6 show soil solution and solid salt concentrations for a condition with 106 cm of total irrigation having a concentration of 10 meq/l in the irrigation water. In this situation the salts added are just slightly more than those removed. After 3 years a stable soil solution concentration was predicted. However, there was a redistribution of solid salts from the surface toward the bottom of the profile.

The model predicts, where the source-sink is important, many management implications. The first implication is that, over a period of time such as a year or two, the soil solution and drainage concentrations will change very little regardless of the irrigation management imposed. Consequently the salt load of the drainage water can be evaluated by measuring the water flow to drainage and multiplying it by the salt concentration of the drainage water. Since the solution concentration of the drainage water changes so slowly, yearly measurements of the solution concentration should be sufficient for purposes of monitoring. Thus, the critical measurement is the total water flow to drainage. This also implies that any experiment designed to measure influences of irrigation management variables in these systems must be carried over many years.

The second implication is that irrigation management could be practiced with no leaching at all. Model predictions indicate this could go on

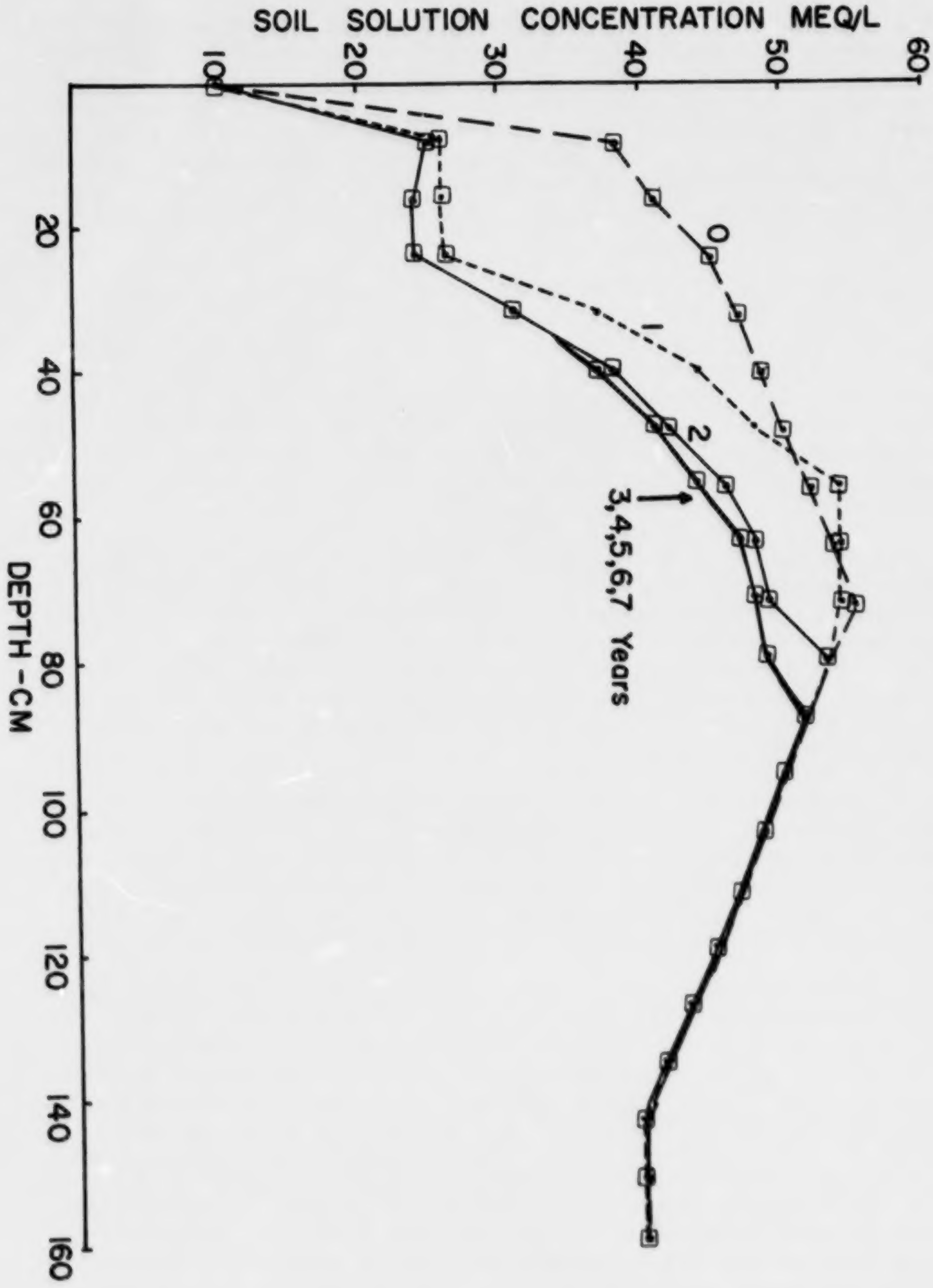

Figure 5. Salt concentration in solution phase as a function of depth and time. Irrigation was 106 cm/yr with poor water quality (10 meq/l).

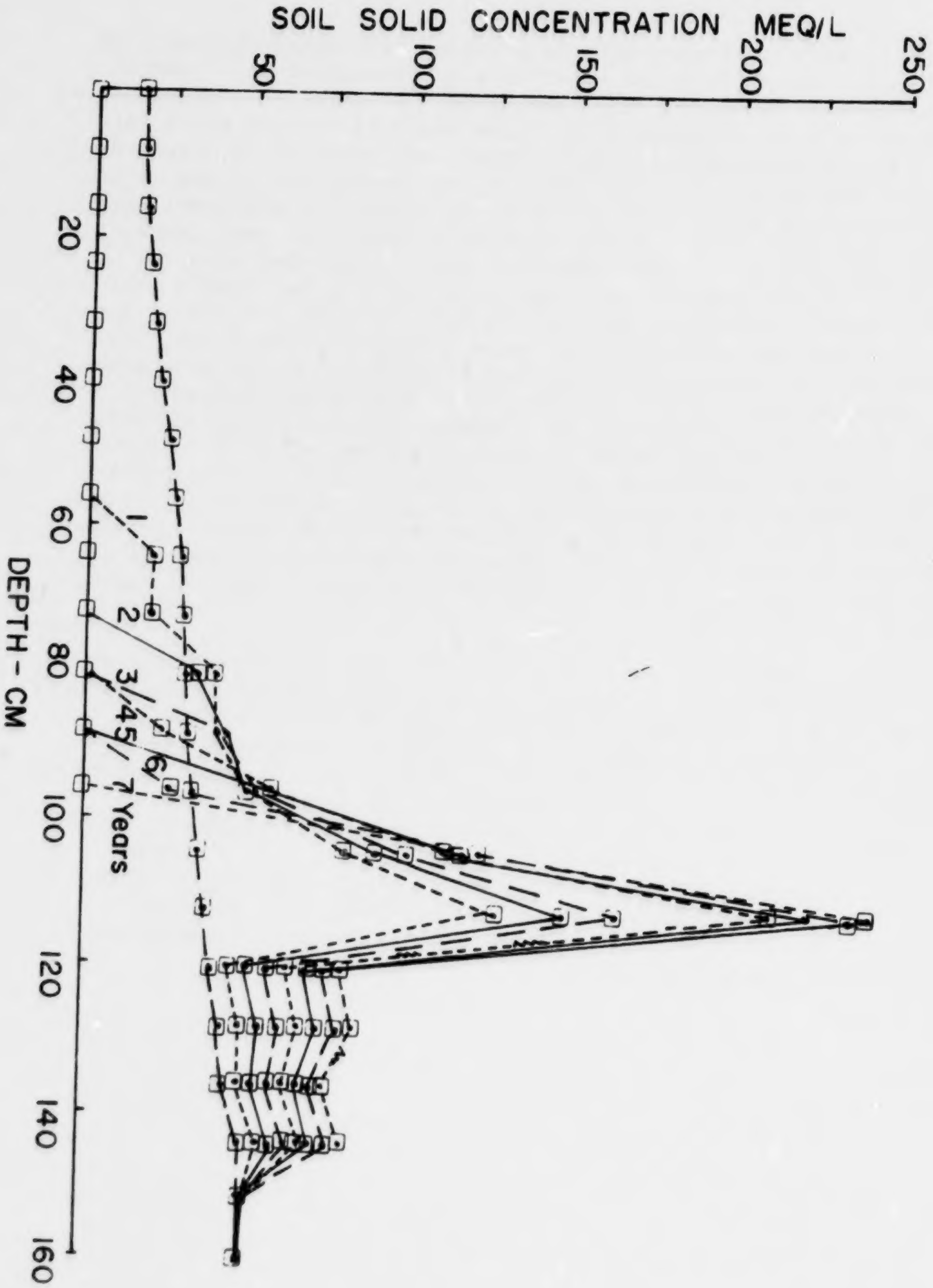

Figure 6: Salt concentration in solid phase as a function of depth and time. Irrigation was 106 cm/yr with poor water quality (10 meq/l).

indefinitely with no adverse effects provided soil water storage plus irrigation and upward flow was equal to evapotranspiration. Caution should be used in accepting this conclusion. If salts were precipitated there would be a limit beyond which there would be no void space left in the soil for solid salt storage. This limit would not be reached for a very long period of time, however. An examination of the irrigation management practices over the years in Ashley Valley, Utah, have indicated that this situation has actually occurred for many years. Irrigation is with gravity systems which apply water with very low uniformity. Farmer practice has been to irrigate a few times a year with high amounts of water. Good yields have resulted. There is a water table near the surface (EC of about 2 mmhos/cm) which supplies water between the infrequent irrigations. The soils in the area are highly permeable which would contribute to a highly variable amount of water moving through the soil on a field. Yet the yields are not variable over the fields. Water moving up from the water table has apparently supplied crop needs in the under-irrigated areas without yield decreases over the years. Most of the salts transported by the water moving up have apparently precipitated out of the soil solution. This process has been going on for about 50 years with no problems with crop production--in fact a very simple and efficient irrigation management system has developed.

To illustrate further the above situation the results of a field experiment of alfalfa conducted in Ashley Valley in 1975 are cited. Salinity variables and irrigation variables were established on mature alfalfa. Six levels of salinity were imposed by adding water with different levels of salt concentration (using calcium chloride) at the beginning of the season with the highest level being 6 mmhos/cm. Water applied was varied from 0 to more than evapotranspiration. There was no influence on alfalfa yields due to either salinity or water application treatment. Water coming from the water table apparently supplied the needs of the plants where no irrigation was applied. There was a difference in soil profile salinity due to treatment near the surface but not below 45 cm.

LITERATURE CITED

Bliesner, R. D., R. J. Hanks, L. G. King and L. S. Willardson. 1976. Effects of irrigation management on the quality of irrigation return flow. Soil Sci. Soc. Amer. Jour.: (Submitted)

Bresler, E. 1973. Simultaneous transport of solute and water under transient, unsaturated flow condition. Wat. Res. Res. 9:975-986.

Bresler, E., and R. J. Hanks. 1969. Numerical method for estimating simultaneous flow of water and salt in unsaturated soils. Soil Sci. Soc. Amer. Proc. 33:827-832.

Childs, S. W., and R. J. Hanks. 1975. Model to predict the effect of soil salinity on crop growth. Soil Sci. Soc. Amer. Proc. 39:617-622.

Dutt, G. R., M. J. Shaffer, and W. J. Moore. 1972. Computer simulation model of dynamic bio-physicochemical processes in soils. Agric. Exp. Sta., University of Arizona, Tucson. Technical Bulletin 196.

Gupta, S. C. 1972. Model for predicting distribution of salt and water in soils. Ph.D. Dissertation, Utah State University.

Gupta, S. C., and R. J. Hanks. 1972. Influence of water content on electrical conductivity in the soil. Soil Sci. Soc. Amer. Proc. 36:855-857.

King, L. G. and R. J. Hanks. 1975. Management practices affecting quality and quantity of irrigation return flow, U. S. Env. Prot. Agency Rpt. EPA-660/2-75-005. 155 pages.

Melamed, D., R. J. Hanks and L. S. Willardson. 1976. Model of salt flow in soil with a source-sink term. Soil Sci. Soc. Amer. Jour. (Submitted)

Nimah, M., and R. J. Hanks. 1973. Model for estimating soil water, plant and atmospheric interrelation. I. Description and sensitivity. II. Field test of the model. Soil Sci. Soc. Amer. Proc. 37:522-527, 528-532.

Oster, J. D. and J. D. Rhoades. 1975. Calculated drainage water compositions and salt burdens resulting from irrigation with river waters of the Western United States. Jour. Env. Qual. 4:73-79.

Smajstrala, A. G., D. L. Tadel, and E. A. Hiler. 1975. Simulation of miscible displacement in soils. Amer. Soc. Agr. Eng. Trans. Vol. 18.

Tanji, K. K., D. L. Redell, G. V. Terry and R. S. Ayres. 1972. Computer simulation analysis on reclamation of salt-affected soils in San Joaquin Valley, California. Soil Sci. Soc. Amer. Proc. 36:127-133.

Warrick, A. W., J. W. Biggar, and D. R. Nielsen. 1971. Simulation of solute and water transfer for an unsaturated soil. Wat. Res. 7(5):1216-1225.

HYDROSALINITY MODELING OF IRRIGATION RETURN FLOW IN THE MESILLA VALLEY, NEW MEXICO

Stephen G. McLin and Lynn W. Gelhar 1/

INTRODUCTION

General Description of Study Area

The Mesilla Valley, an alluvial valley adjacent to the Rio Grande in southern New Mexico, extends approximately 60 miles (97/cm) from Seldon Canyon to El Paso Canyon and has a maximum width of about five miles (8/cm) (see Figure 1). The valley encompasses about 108,000 acres (72,800 ha). The major population center is Las Cruces, New Mexico with El Paso, Texas immediately south of the area. The valley has fairly level topography with a relatively smooth alluvial floodplain ranging in width from a few hundred feet to about five miles; it is bordered by steep bluffs 50 to 100 feet (15 to 30 m) high, composed of loosely cemented sand, silt, clay, and gravel. Recent alluvium about 100 feet (100 m) thick forms the primary aquifer; it is underlain by basin fill deposits (Santa Fe Group) which also yield substantial amounts of water.

The climate of the valley is predominantly semi-arid. It is characterized by clear and sunny days, large diurnal temperature ranges, low humidity, and scant rainfall. The mean annual precipitation averages less than 10 inches (250 mm), with a maximum of about 18 inches (460 mm) and a minimum of about three inches (75 mm). Most of the rain usually falls in summer when tropical air masses from the Gulf of Mexico move over the area and cause thunderstorms. These showers are occasionally accompanied by hail, which may severely damage crops. The high temperature and low humidity lead to rapid evaporation of rainfall.

Objective

The overall objective of this study is to implement and test a computer-based mathematical model of irrigation-related water quality in the Mesilla Valley. The model, which was developed by the U. S. Bureau of Reclamation (1975b) for the Environmental Protection Agency, can represent a general water and mass balance for a river basin or portion thereof. The model includes components which simulate surface and groundwater reservoirs, diversions to meet irrigation needs and other uses, irrigation return flows, and chemical transformations in the soil. Several nodes can be used to simulate the conditions in different segments of a basin. The model would be classified as a multi-celled lumped parameter model. Input data on water use, surface and groundwater quality, and streamflows and diversions are required to operate the model.

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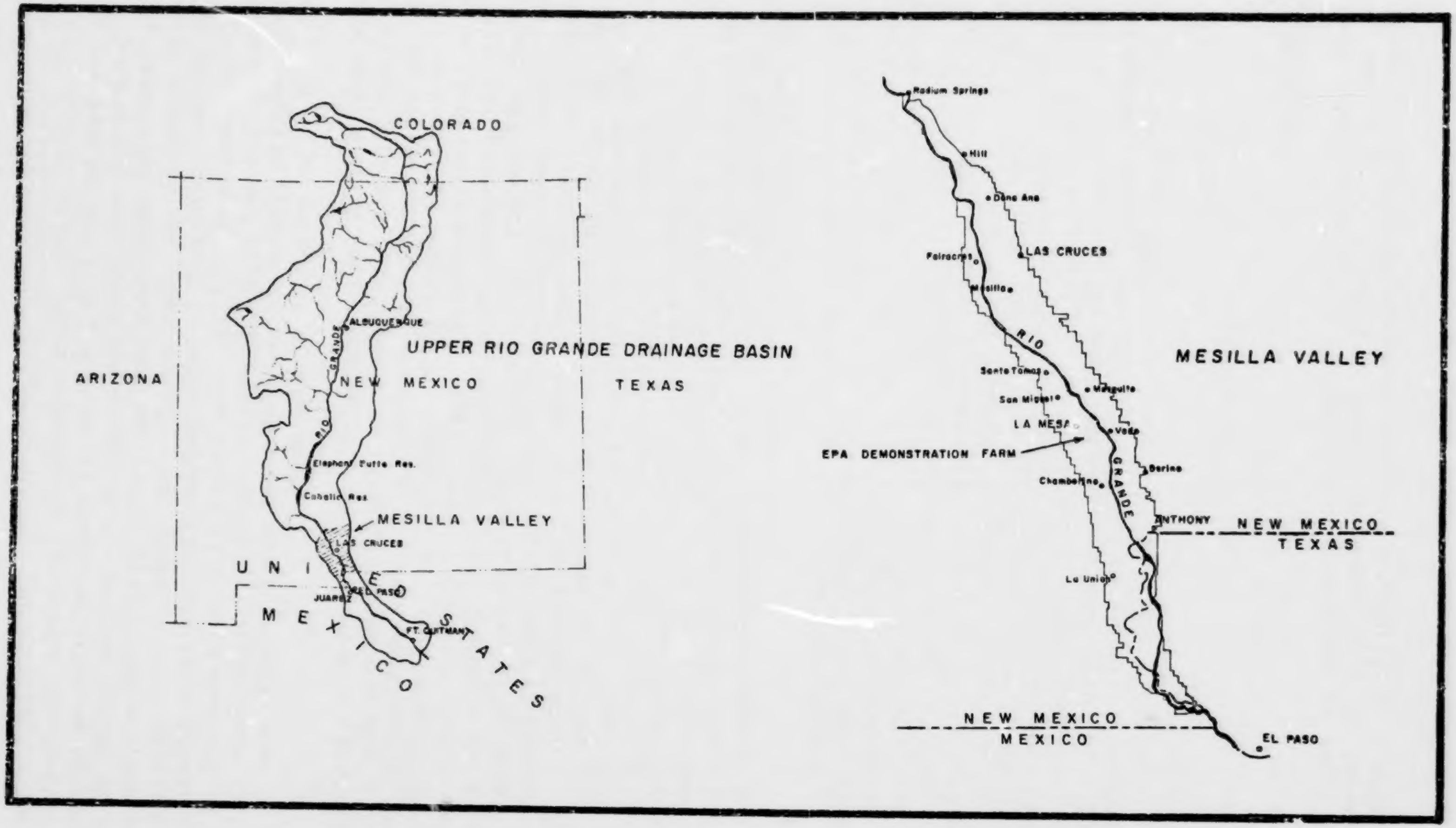
COLORADO
UPPER RIO GRANDE DRAINAGE BASIN
ARIZONA
NEW MEXICO
TEXAS
ALBUQUERQUE
RIO GRANDE
Elephant Butte Res.
Caballo Res.
MESILLA VALLEY
LAS CRUCES
UNITED STATES
MEXICO
EL PASO
JUAREZ
FT. QUITMAN
MESILLA VALLEY
Radium Springs
Hill
Dona Ana
LAS CRUCES
Fairacres
Mesilla
RIO GRANDE
Santo Tomas
San Miguel
Mesquite
LA MESA
Vado
EPA DEMONSTRATION FARM
Berino
Chamberino
ANTHONY
NEW MEXICO
TEXAS
La Union
NEW MEXICO
MEXICO
EL PASO

Figure 1. Location of irrigation return flow salinity control demonstration farm in the Mesilla Valley and Upper Rio Grande drainage basin, New Mexico.

A review of the literature on irrigation return-flow modeling was an integral part of this effort. Much emphasis in irrigation return-flow modeling has been on the flow and chemical characteristics in the near-surface unsaturated zone above the water table. Hornsby (1973) reviews modeling techniques which have been applied to predict the quality of irrigation return flows. Examples of recent computer-based models of moisture and salt transport in soils include King and Hanks (1973) and Dutt, Shaffer, and Moore (1972). The latter represents chemical equilibrium of major ions and a kinetic approach to the nitrogen cycle in the soil. The soil chemistry portion of the USBR model which is being used in the current study is an outgrowth of that model.

When one considers the large volumes of water in groundwater storage, it is evident that aquifers underlying irrigated areas can play a central role in irrigation return-flow quality. At a recent workshop on irrigation return-flow modeling, Walker (1975) noted the need for improved information on groundwater behavior. Several recent modeling studies have emphasized the groundwater flow in salinity models (Maddaus and Aaronson, 1972; Lyons and Stewart, 1973; Konikow and Bredehoeft, 1974; Hassan et al., 1974); these models all represent two-dimensional horizontal flow with total dissolved solids taken as a conservative solute. In contrast, the Bureau of Reclamation (Shaffer, Ribbens and Huntley, 1975) consider two-dimensional groundwater flow in a vertical plane and chemical equilibrium for major ions. Gupta, Tanji, and Luthin (1975) have developed a three-dimensional groundwater flow and quality model assuming conservative solute. Lumped parameter groundwater flow and quality models have been used by Gelhar and Wilson (1974) and Mercado (1976); these models are similar to the structure implicit in the groundwater portion of the USBR-EPA model being used in the current study.

Described in the following sections are the activities relating to the implementation and evaluation of the USBR-EPA model for the Mesilla Valley. Included are a summary of the model structure and documentation of the program revisions required to operate the program on an IBM system. The model setup for the Mesilla Valley is developed and the existing data base and current sampling program are described. Features of the consumptive use estimates and some initial analysis of aquifer properties are discussed. The testing of the model for the Vernal, Utah case study is then outlined. Results of preliminary simulations for the Mesilla Valley are presented. Finally, a sensitivity analysis is performed in order to examine the model's response to variations of several important physical features. The major results are summarized, especially as related to expected direction of future work with the model.

HYDROSALINITY MODEL

Model Structure

The USBR model represents an irrigated area by a series of small subunits, each of which is called a node. The number of nodes depends on the physical features of the study area, the availability of data, and the number of points at which the model response is desired within the area. The model structure is based on a water balance for a given time interval which is computed and maintained for each node. The transfer of water between the river and aquifer is essential to maintain this balance. A soil column is included to simulate the chemical exchange between soil and water as water percolates down through the soil column. The model allows the mixing of one water with another, and computes the chemical quality of the mixed waters in proportion to the volumes mixed. Thus a chemical mass balance is simultaneously maintained. All these computations are performed for one node at a time and progress from the upstream to the downstream nodes.

A node includes simulation of several features as shown in Figure 2. These are: simulation of magnitude and quality of river flow, diversion to meet the irrigation demand, water transfer between the river and aquifer, irrigation return flows directly to the aquifer, through the soil to the aquifer, and to the river. The river flow at the start of nodal operation is a known quantity, a portion of which is diverted to meet the irrigation demand. The irrigation return flow is then computed by subtracting the crop consumptive use from the irrigation demand. The chemical quality of mixed waters is computed at each point. At the end of a nodal operation, the balance of inflow to and outflow from the river is determined. If the river flow is in excess of that observed, the additional water is transferred to the aquifer; if the river flow is in deficit, water is withdrawn from the aquifer to maintain the balance. In the model operation no consideration is given to spatial variability of hydrologic variables within a node. Hydraulic properties of the soil and aquifer are not considered.

The input data needed to operate the model include irrigation demand, crop consumptive use, diversion, river water quality, initial aquifer water storage and chemical quality, soil moisture content and its chemical quality and precipitation.

Originally, the computer program for the model was written for a Control Data Corporation computing system. To make the program compatible with an IBM 360-44 system, numerous changes involving definition of variables, and format and dimension statements were required. The revised computer program is listed in a recent report (Lansford et al., 1976) with all of the program changes identified.

Preliminary Model Structure for the Mesilla Valley

The objectives of these simulations are to determine what model structure is suitable for the Mesilla Valley and to test the sensitivity of the model results to observed and estimated input data. The model was implemented with existing field data for the period June 1967 to June 1968. A complete set of groundwater quality data was available at the beginning of this period.

The irrigated areas served by the Leasburg and Mesilla diversion dams form natural nodes for the model (see figure 3). The quantity and chemical

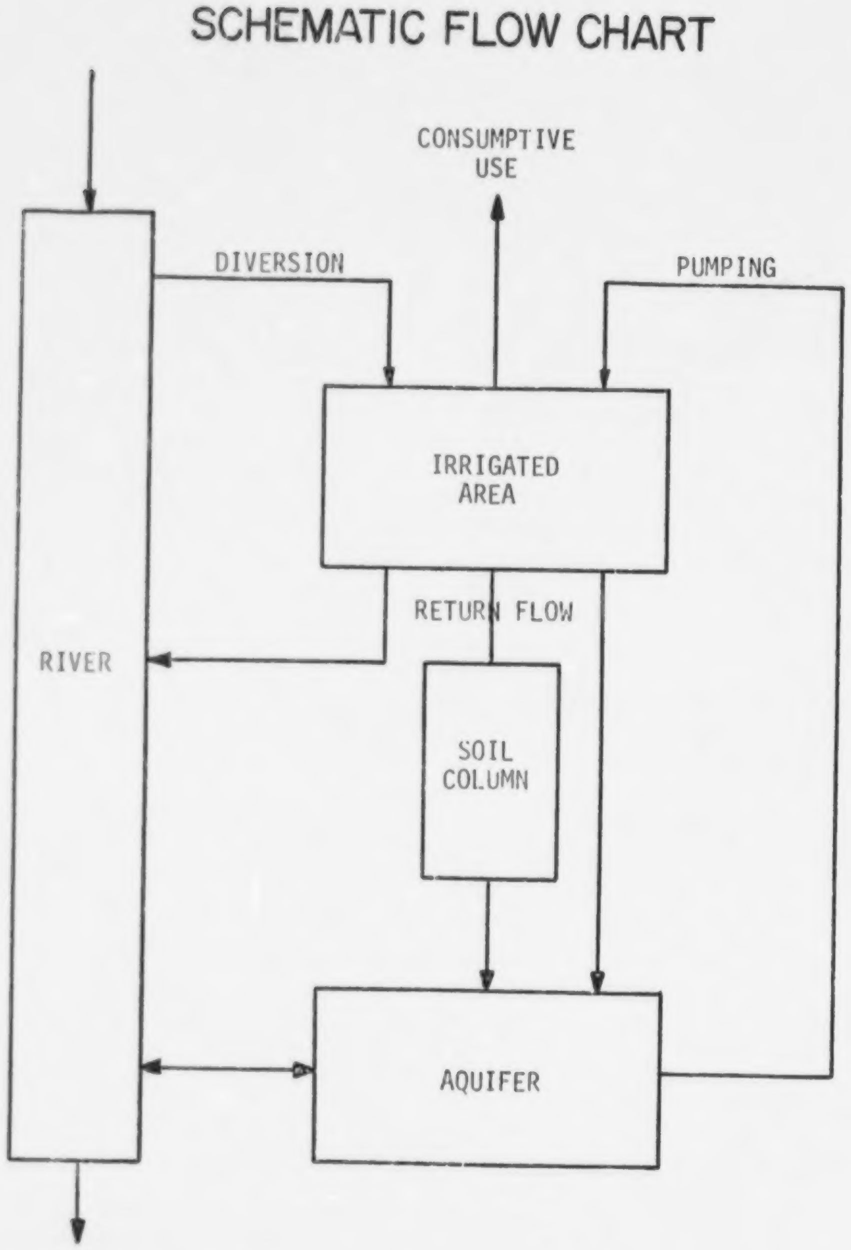
SCHEMATIC FLOW CHART
CONSUMPTIVE USE
DIVERSION
PUMPING
IRRIGATED AREA
RETURN FLOW
RIVER
SOIL COLUMN
AQUIFER

Figure 2. Schematic flow chart showing the features simulated in each node of the model.

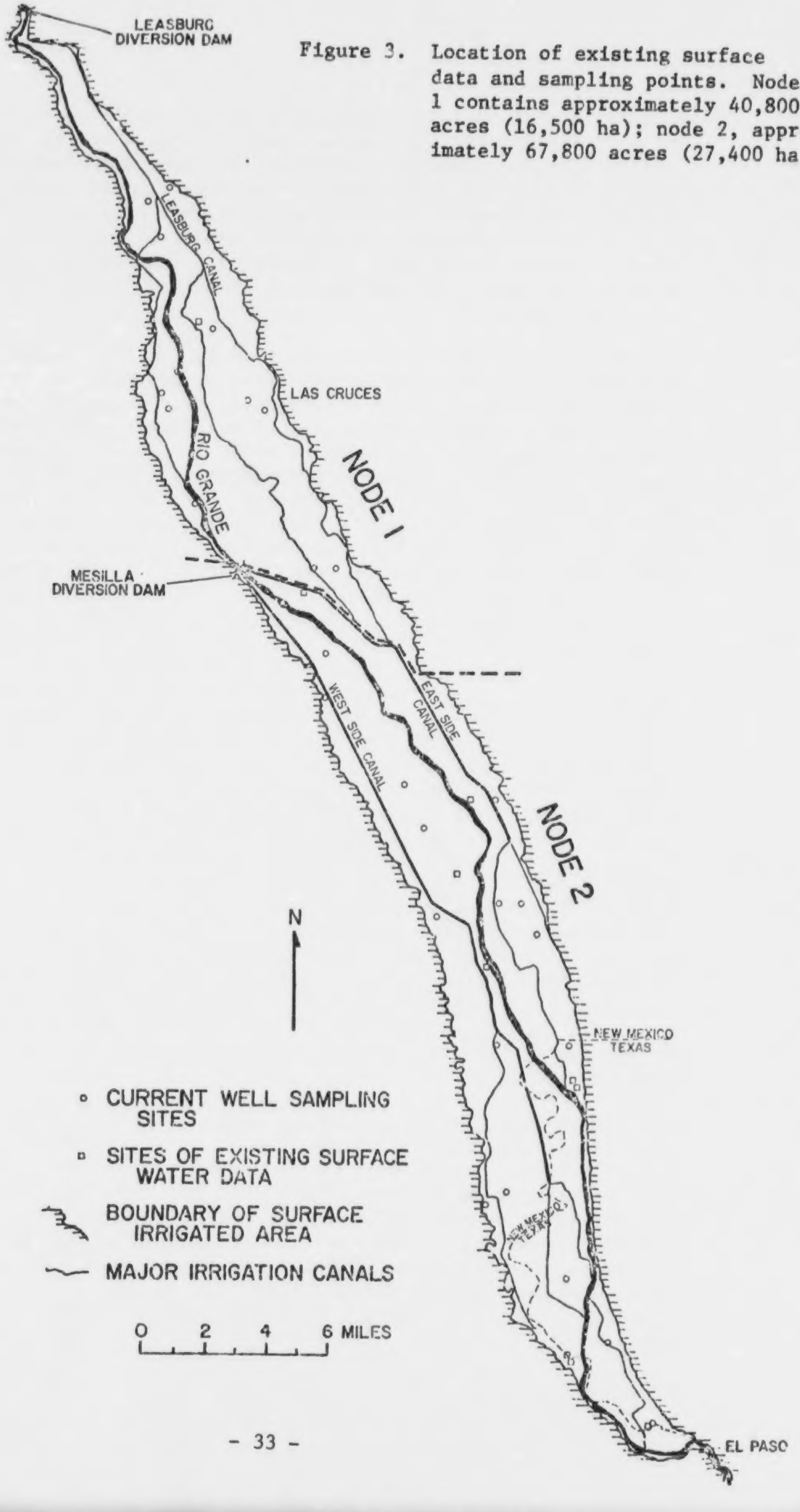
LEASBURG DIVERSION DAM
LEASBURG CANAL
LAS CRUCES
RIO GRANDE
NODE 1
MESILLA DIVERSION DAM
EAST SIDE CANAL
WEST SIDE CANAL
NODE 2
N
NEW MEXICO
TEXAS
NEW MEXICO
TEXAS
EL PASO
CURRENT WELL SAMPLING SITES
SITES OF EXISTING SURFACE WATER DATA
BOUNDARY OF SURFACE IRRIGATED AREA
MAJOR IRRIGATION CANALS
0 2 4 6 MILES

Figure 3. Location of existing surface data and sampling points. Node 1 contains approximately 40,800 acres (16,500 ha); node 2, appr imately 67,800 acres (27,400 ha

quality of flow in these diversions are observed. Each node includes several operational features as shown in Figure 4. The nodal configuration and its subsequent operation are best described by a sequence of operations that actually occur. Each operation is assigned a sequence number in the order that it takes place (see Figure 4). In the assignment of sequence numbers, a positive number is assigned to inflow and a negative number to outflow or diversion. The configuration of operations in node 1 is about the same as in node 2 so only node 1 is explained here (see Figure 4).

At the upstream end of node 1 the flow in the Rio Grande is observed. The portion of this riverflow diverted at Leasburg is also observed. The river flow remaining after diversion is then computed; this quantity of flow is not available for irrigation use within node 1 and therefore is diverted from the node through sequence 1. The irrigation demand for crops in the area is computed independently, using the USBR program EVPCOM and the overall irrigation efficiency. If the amount of surface water diversion is not sufficient to meet the demand additional water is pumped from the aquifer. Originally, this feature was not available in the model input data set-up; the model would satisfy the demand either entirely by surface water or groundwater. This feature, presently included in the model through the input data, is more realistic because both groundwater and surface water are used to meet the demand. However, no changes were made in the program as a consequence of this added feature. Then the return flow, the difference between the demand and the consumptive use, is calculated in the program. A part of this return flow will go to the river and a part to the aquifer through the soil. Once the return flow mixes with river flow (after diversion) the chemical quality of river flow is updated; this river flow is identified as the predicted river flow. At the downstream end of the node, the river flow, a combination of the flows from El Paso carriage and waste, Del Rio drain, and the Rio Grande at Mesilla dam, is observed. A comparison is made between this observed flow and the predicted river flow to establish the required water transfer between river and aquifer. If the predicted flow is higher than the observed flow, the model forces a transfer of water from river to aquifer. If the predicted flow is lower than the observed flow, a transfer of water from aquifer to river is required. This exchange mechanism is essential to accomplish the hydrologic balance. When the exchange is made, the chemical quality of flow is updated simultaneously. Finally, at the end of the nodal operation, the model yields flow and its chemical quality.

The monthly input data used to operate the model include: observed river flow at the upstream end of the node and its chemistry, the amount of water diverted at Leasburg, crop consumptive use and irrigation efficiency, data on percentage of return flow going to river and to aquifer, initial aquifer water storage and chemical quality, and observed river flow at the downstream end of the node including flows to and from El Paso carriage and waste, Del Rio drain, and Rio Grande at Mesilla dam, and soil chemistry. These are described in detail below.

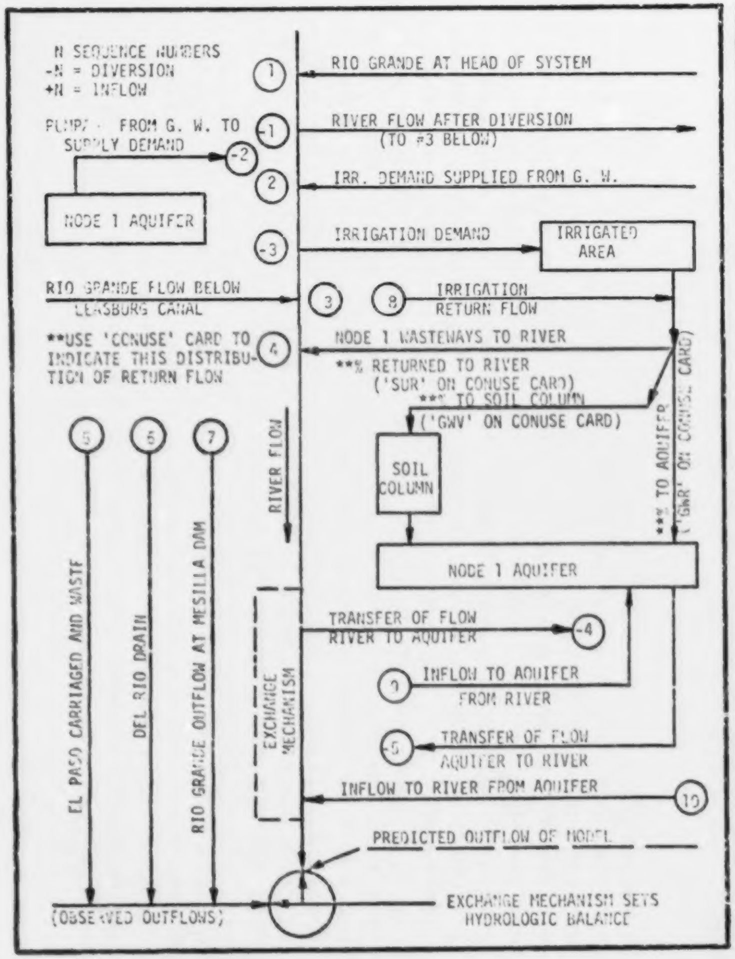
N SEQUENCE NUMBERS
-N = DIVERSION
+N = INFLOW
PUMPAGE FROM G. W. TO SUPPLY DEMAND
-2
NODE 1 AQUIFER
1
RIO GRANDE AT HEAD OF SYSTEM
-1
RIVER FLOW AFTER DIVERSION (TO #3 BELOW)
2
IRR. DEMAND SUPPLIED FROM G. W.
-3
IRRIGATION DEMAND
IRRIGATED AREA
RIO GRANDE FLOW BELOW LEASBURG CANAL
3
8
IRRIGATION RETURN FLOW
**USE 'CONUSE' CARD TO INDICATE THIS DISTRIBUTION OF RETURN FLOW
4
NODE 1 WASTEWAYS TO RIVER
**% RETURNED TO RIVER ('SUR' ON CONUSE CARD)
**% TO SOIL COLUMN ('GWV' ON CONUSE CARD)
**% TO AQUIFER ('GWR' ON CONUSE CARD)
RIVER FLOW
SOIL COLUMN
5
6
7
EL PASO CARRIAGED AND WASTE
DEL RIO DRAIN
RIO GRANDE OUTFLOW AT MESILLA DAM
NODE 1 AQUIFER
EXCHANGE MECHANISM
TRANSFER OF FLOW RIVER TO AQUIFER
-4
9
INFLOW TO AQUIFER FROM RIVER
-5
TRANSFER OF FLOW AQUIFER TO RIVER
INFLOW TO RIVER FROM AQUIFER
10
PREDICTED OUTFLOW OF MODEL
(OBSERVED OUTFLOWS)
EXCHANGE MECHANISM SETS HYDROLOGIC BALANCE

Figure 4a. Mesilla Valley system flow chart--node 1

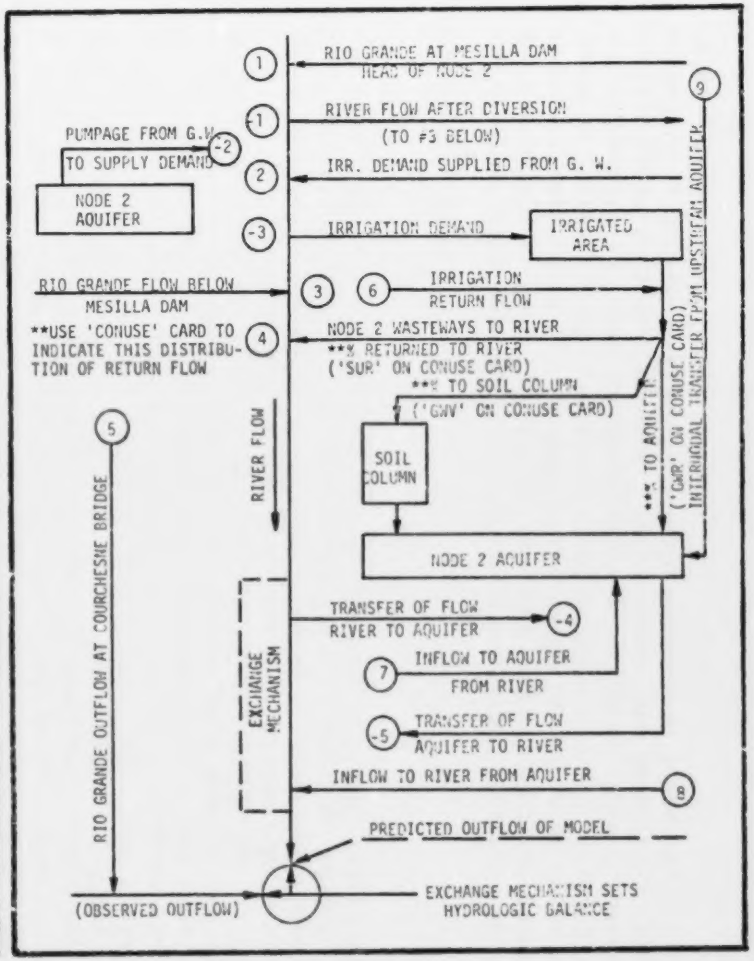
1
RIO GRANDE AT MESILLA DAM HEAD OF NODE 2
9
PUMPAGE FROM G.W. TO SUPPLY DEMAND
-2
-1
RIVER FLOW AFTER DIVERSION (TO #3 BELOW)
NODE 2 AQUIFER
2
IRR. DEMAND SUPPLIED FROM G. W.
-3
IRRIGATION DEMAND
IRRIGATED AREA
RIO GRANDE FLOW BELOW MESILLA DAM
3
6
IRRIGATION RETURN FLOW
**USE 'CONUSE' CARD TO INDICATE THIS DISTRIBUTION OF RETURN FLOW
4
NODE 2 WASTEWAYS TO RIVER
**% RETURNED TO RIVER ('SUR' ON CONUSE CARD)
**% TO SOIL COLUMN ('GWV' ON CONUSE CARD)
**% TO AQUIFER ('GWR' ON CONUSE CARD)
INTERNODAL TRANSFER FROM UPSTREAM AQUIFER
5
RIO GRANDE OUTFLOW AT COURCHESNE BRIDGE
RIVER FLOW
SOIL COLUMN
NODE 2 AQUIFER
EXCHANGE MECHANISM
TRANSFER OF FLOW RIVER TO AQUIFER
-4
7
INFLOW TO AQUIFER FROM RIVER
-5
TRANSFER OF FLOW AQUIFER TO RIVER
INFLOW TO RIVER FROM AQUIFER
8
PREDICTED OUTFLOW OF MODEL
(OBSERVED OUTFLOW)
EXCHANGE MECHANISM SETS HYDROLOGIC BALANCE

Figure 4b. Mesilla Valley system flow chart--node 2

Reproduced from best available copy.

DATA BASE AND ANALYSIS

Existing Data Base

Surface water data for the Mesilla Valley during the last 50 years are extensive (see Lansford et al., 1976, for example); data collection sites are shown on Figure 3. Long-term records of flow rate are available for most parts of the Mesilla Valley, except for the Rio Grande at the Mesilla dam. The latter information would be useful as a water balance check point for node 1, but the data are not required to operate the model. The data on chemical quality are fairly complete for the Rio Grande at the Leasburg dam and at El Paso. A fair portion of the water quality data is either in the form of electrical conductivity or total dissolved solids. The main drains (Selden, Picacho, Del Rio, La Mesa, East, and Montoya) have a long record of flow rates but a short record of water quality (this is usually either electrical conductivity or total dissolved solids). Irrigation diversions (Leasburg, East Side, and West Side canals) have excellent long-term flow-rate records but no chemical records. It is assumed that the Leasburg canal chemical quality is the same as that of the Rio Grande at the Leasburg dam and that the East Side and West Side Canal chemistries are the same as that of the Rio Grande at the Mesilla dam. Agencies that have provided or helped to provide surface water data are the Bureau of Reclamation and the International Boundary and Water Commission, both at El Paso, Texas. Wilcox (1968) and Scofield (1938) were also sources of useful surface water data.

The groundwater data are less complete than the surface water data. The only long-term month-by-month measurements of water levels are done by the Bureau of Reclamation in Las Cruces, New Mexico. They measure water levels in 40 observation wells. The chemical quality of these well waters was measured only once, during late May and early June 1967 (Basler and Alary, 1968). Otherwise the records of groundwater levels and quality are sporadic. Either the well data are not uniformly distributed throughout the valley for any given month, or any given well does not have a long continuous month-by-month or year-by-year record. Water level and quality data were obtained from the U. S. Geological Survey branch offices in Las Cruces, New Mexico, and El Paso, Texas, the El Paso Water Utilities Public Service Board in El Paso, Texas and from the following publications: Basler and Alary (1968), Conover (1954), Busch and Hudson (1964-73), Leggat, Lowery, and Hood (1962), King, Hawley, Taylor, and Wilson (1969, 1971), and Richardson (1971).

Sampling Program

The current sampling program emphasizes groundwater quality. Water samples are taken from at least 25 shallow two-inch (53 mm) diameter observation wells which are maintained by the USBR or the USGS; locations of these wells are shown in Figure 3. The wells are sampled using a one-pint (0.451) bailer and are bailed at least 20 times before a sample is taken to assure that aquifer water is being obtained. Water levels are measured in each well before it is bailed. Electrical conductivity and temperature are measured in the field.

Surface water samples are obtained at 10 locations as shown in Figure 3; electrical conductivity and temperature are measured on site. The water samples are analyzed by the soil and water testing lab at NMSU; laboratory analyses include conductivity, pH, Mg, Na, K, Ca, Cl, HCO_3, CO_3, and SO_4. A few check samples are also analyzed at the water chemistry laboratory of the Bureau of Mines and Mineral Resources at New Mexico Tech. Some systematic differences (up to 20 percent) between some of the analyses of individual ions from the two laboratories have been found. Additional check analyses are planned, and on-site measurements of pH, HCO_3, and possible dissolved CO_2 will be used to improve the chemical analyses.

There were two on-going studies which will compliment the data base for the current project. A USGS study, directed by C. A. Wilson at Las Cruces, is providing new field information on groundwater conditions, especially in the Santa Fe formation which underlies the shallow alluvial aquifer. The work involves drilling, geophysical logging, test pumping, and water-quality sampling for several wells a few thousand feet in depth. The results will be helpful in estimating the depth of the alluvial aquifer and the interchange of water between the shallow and deep aquifers. Another study sponsored by the U. S. Bureau of Reclamation and directed by Dr. John W. Hernandez at New Mexico State University includes monitoring of surface water quality at 15 locations on drains and the river in the Mesilla Valley. This project involved sampling at five times during 1975; complete water analyses included trace metals, pesticides, oxygen demand, and coliform bacteria.

Data Analysis

The Theissen polygon method was used to estimate the initial values of aquifer volume and the average chemical quality for each node. This method was chosen because it yields fixed weighting factors for a given configuration of wells. The data for the aquifer initial chemical conditions are from Basler and Alary (1968). They obtained this data during late May and early June 1967, from 40 U. S. Bureau of Reclamation observation wells located in the Mesilla Valley. Since this report contained the only comprehensive set of chemical analyses for the entire valley, it was chosen for the determination of aquifer initial conditions.

The initial storage in the alluvial aquifer was estimated using the observed depth to water in the observation wells weighted according to the factors determined from the Theissen polygons. The base of the alluvial aquifer was taken to be 80 feet (24 m) below the ground surface and a specific yield of 20 percent was used to calculate the storage in the aquifer.

The consumptive use of crops in the Mesilla Valley is estimated by the modified Jensen-Haise method (Jensen, Robb, and Franzoy, 1970) with the program EVPCOM prepared by the U. S. Bureau of Reclamation (1974). This method first evaluates potential evapotranspiration from air temperature and solar radiation data. By multiplying potential evapotranspiration by a crop coefficient, a specific estimate of evapotranspiration is obtained, and this is the estimated crop consumptive use. The crop coefficient not only varies from one crop to another but also varies for the same crop with

Table 1. Crop consumptive use (acre-feet/acre) Mesilla Valley based on the Jensen-Haise method for computing evapotranspiration, using daily mean temperature and solar radiation for El Paso, Texas.

	1967	1968
JAN	.008	.008
FEB	.006	.007
MAR	.146	.036
APR	.218	.168
MAY	.326	.328
JUN	.374	.362
JUL	.709	.639
AUG	.770	.759
SEP	.664	.632
OCT	.452	.457
NOV	.001	.106
DEC	.001	.001
TOTAL CONSUMPTION USE	3.675*	3.503+
TOTAL CROPPED ACRES (has)	74662(30218)	82820(33512)

* 11,200 m^3/ha

+ 10,700 m^3/ha

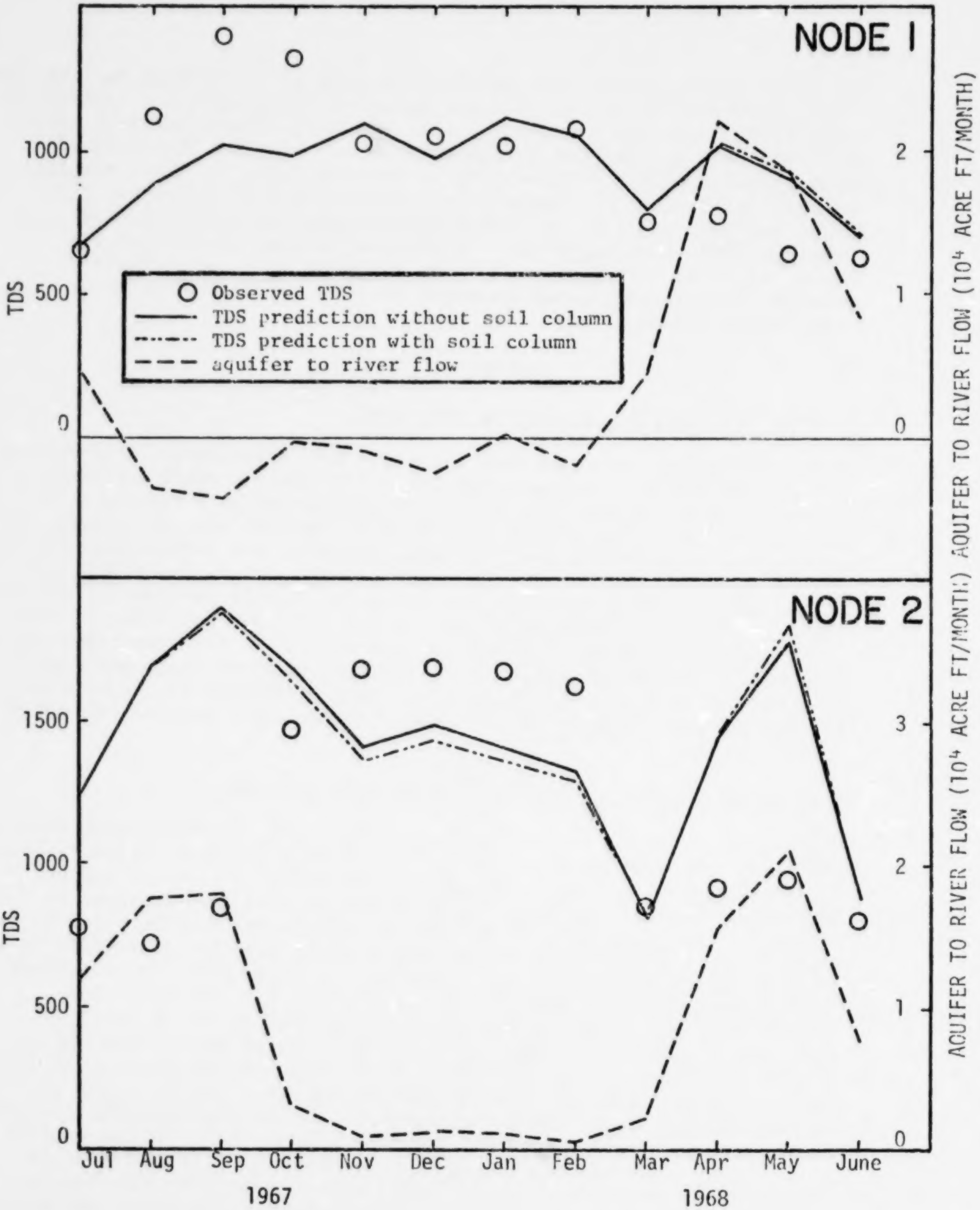

Figure 5. Model predictions for July 1967 to June 1968

the stage of its growth. One modification made in the program was that the crop coefficient was set to zero for the non-growing season; originally a value of 0.15 was used for that period. The temperature and solar radiation data used in computing the consumptive use computed by the Jensen-Haise method for the Mesilla Valley is shown in Table 1. These results are much higher than the commonly accepted estimate of around two feet (0.6m) per year based on the Blaney-Criddle equation (Henderson and Sorenson, 1968; Lansford et al., 1973). The present consumptive use values should be viewed as preliminary estimates which will require thorough re-evaluation using lysimeter data and actual soil-moisture observations (USBR, 1974).

ANALYSIS OF RESULTS

Test of the Model for the Vernal Case Study

With the computer revisions made and the appropriate changes incorporated, it was necessary to test the model and see whether it would reproduce previously obtained results. The model results for an irrigated area near Vernal, Utah (USBR, 1975, Vol. 1) were used in this evaluation. An attempt was then made to test the model both with and without soil column for the period April 1971 through October 1972. It was found that the model, in the existing form, would not reproduce the results provided by the USBR. The reason for the discrepancy was that the model did not allow an internodal transfer of water from the upstream aquifer to the downstream aquifer. When this provision was added to the computer program, the model produced results identical to the USBR results. Much difficulty was experienced in testing the model because of the lack of sample input data set-up and a sample problem.

Preliminary Simulation Results for the Mesilla Valley

With the input data and the previously described operational procedure, the model was programmed to simulate the monthly response of the Mesilla Valley system. The model response for both nodes in terms of TDS (total dissolved salts) in ppm from July 1967 through June 1968 is shown in Figure 5. The transfer of water between the aquifer and the river is also shown. The observed and predicted TDS differed greatly, especially in node 2; however, the differences are comparable to those found in the Vernal verification study for node 3 (USBR, 1975, Vol. 1). The model definitely does not reproduce the observed time history of TDS variation; this same type of discrepancy was found in previous applications of the model. From Figure 5, it is evident that large discrepancies occur when large transfers of water from the aquifer are being forced by the water-balance feature of the model. We suspect that the discrepancies are produced primarily by the transfer of high salinity water from the aquifer to the river. Considering the aquifer parameters, it is difficult to justify water transfers of up to 20,000 acre-feet(24,7000,000m^3)/month. Model improvements which relate the stream-aquifer properties and aquifer water level will be considered in future work. In addition the length of the test period will be extended to between 30 and 50 years in order to evaluate the ability of the model to reproduce observed long terms changes in return flow water quality.

The effects of the chemical changes in the soil were also tested in the preliminary runs. Initially, the soil chemistry data for the Vernal study were used to test the functioning of the subroutine SOILCO. The chemical transformations in the soil introduce only very minor changes. We have also made some runs using the preliminary soils data for the Mesilla Valley. These data also had very little effect, as is illustrated in Figure 5.

The consumptive use estimates which were used in these preliminary simulations are probably somewhat high, as previously discussed. A relatively high irrigation efficiency of 75 percent was also assumed, so that the actual irrigation requirement is more reasonable. Our experience has shown that the model is quite sensitive to consumptive use and irrigation efficiency. These and other factors are examined in detail below.

Sensitivity Analysis

In order to examine the effects of several physical features on the predicted model output, a preliminary model sensitivity analysis was performed. The features examined included the effects of: (1) a 25% reduction in the initial aquifer pore volume, (2) a 50% reduction in the initial chemical concentration of aquifer waters, (3) an average crop consumptive use of 2 ft(0.6m)/yr with an irrigation efficiency of 50%, and (4) a 50% increase in the initial chemical concentrations in the soil. The hydrosalinity model computer program was run using the same data input as before, but making the necessary changes as noted above. Necessary computer runs were made to simulate the effects of the model with and without the soil chemistry subroutine operating.

For the simulation period of July 1967 to June 1968, the sensitivity analysis showed that for a 25% reduction in aquifer pore volume there was no appreciable difference from the original predicted TDS output. The effects of the soil chemistry also made no appreciable difference from the original predicted TDS output. Thus if the time history of predicted TDS output were plotted, it would look almost identical to Figure 5.

When the initial concentration in aquifer waters was reduced, large systematic differences of several hundred ppm per month were noticed, as compared to the original predicted TDS output. These effects can be seen in Figure 6. Changing the irrigation efficiency and crop consumptive use also produced systematic differences in predicted TDS output, as seen in Figure 6. The transfer of water from the aquifer to the river was practically unchanged, and so are not shown in Figure 6. In both of these cases in Figure 6, the effects of the soil chemistry subroutine have also been omitted for clarity, since these effects were only minor.

The soil chemistry increases produced only minor differences in TDS from that originally predicted for NODE 1. The NODE 2 differences are somewhat larger, as seen in Figure 7, but the effects are still relatively minor.

Of the features examined in the sensitivity analyses for the one year simulation period, it is evident that the average initial chemistry of

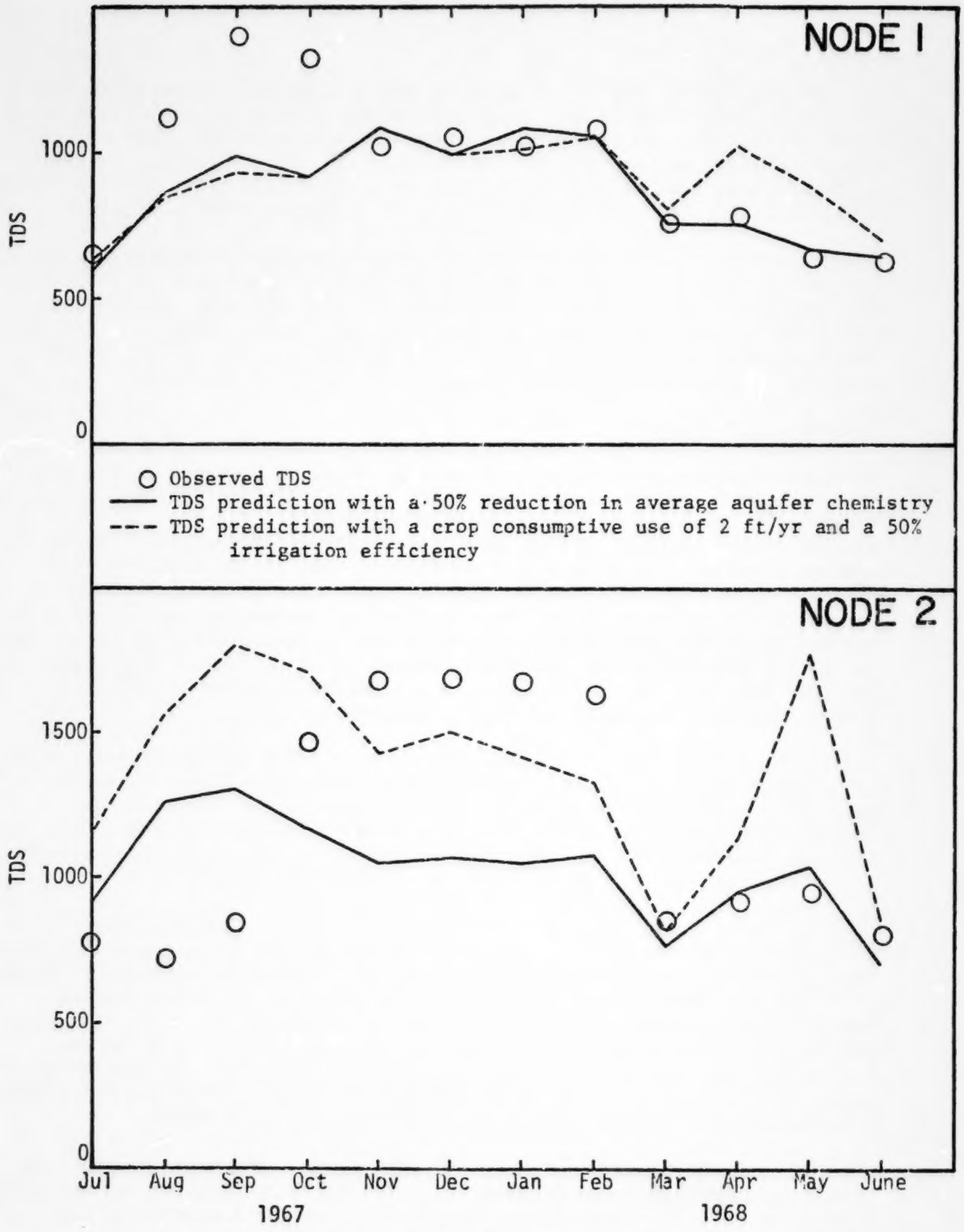

Figure 6. Sensitivity analysis showing the effects of a 50% reduction in initial aquifer chemistry; and the combined effects of an average consumptive use of 2 ft/yr and a 50% irrigation efficiency.

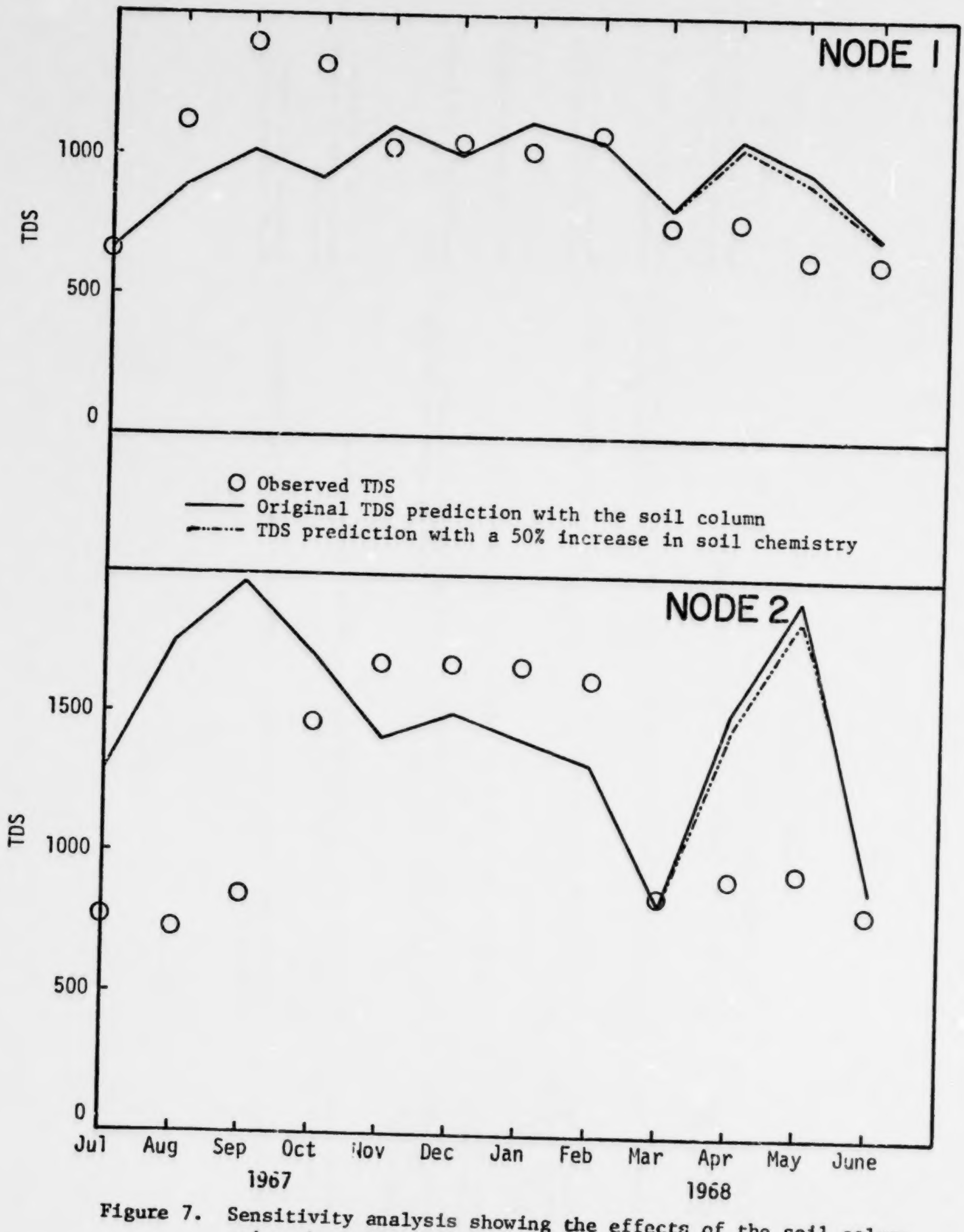

Figure 7. Sensitivity analysis showing the effects of the soil column using the original soil chemistry data; and for a soil chemistry of 1.5 times the original.

TABLE 2. Summary of major model features.

MODEL FUNCTION	IMPLIED LIMITATION	DATA REQUIRED	COMMENTS
Multi-cell lumped parameter model will accept up to 20 cells (or nodes)	All variables are functions of time only	See following	Number of nodes depends on available data and physical features of area
Irrigation water balance to compute return flow	Deals with monthly average over nodal area	Diversion, irrigation demand, GW pumpage, irr. eff., consumptive use, % of return to aquifer and to river	Much of required data is hypothetical
Irrigation water chemistry represented by eight chemical constituents and TDS (Ca^{++}, Mg^{++}, Na^{+}, Cl^{-}, $SO_4^{=}$, HCO_3^{-}, $CO_3^{=}$, NO_3^{-})	Deals with monthly average over nodal area	Surface diversion chemistry and GW chemistry	Chemistry based on volume proportion of waters mixed
Soil moisture movement thru as many as 10 soil column segments	Steady forced displacement each month	Soil moisture content	Optional feature of model
Soil chemistry includes reactions involving Ca^{++}, Mg^{++}, Na^{+}, $SO_4^{=}$, HCO_3^{-}, $CO_3^{=}$, and undissolved $CaSO_4$ and $MgSO_4$	Chemical equilibra approach where extended Debye-Huckel theory applies	Soil chemical analysis, cation exchange capacity, gypsum concentration	Neglects reactions involving Cl^{-} and NO_3^{-}
Aquifer balance transfers water to or from surface and to downstream nodal aquifer(s)	Transfer of flow between river and aquifer is forced to maintain water balance	Initial aquifer volume	River-aquifer transfer should depend on aquifer water level
Aquifer chemistry included in simulation	Uniform aquifer chemistry throughout an entire node	Average initial aquifer chemistry	Equivalent to a "well-mixed" reservoir assumption

aquifer waters and the combined effects of crop consumptive use and irrigation efficiency play an important role in the predicted TDS output.

SUMMARY

Our experience with the USBR-EPA simulation model has demonstrated the difficulty of routine application of large and complex computer-programs even when the model is designed to be general and flexible. This model is actually computer- and site-specific; several subroutines must be modified for each application and this requires substantial knowledge of the logic of the entire program.

The preliminary simulation results for the Mesilla Valley indicate a need to improve the input data and model structure. Several sensitivity analyses conducted with the model in its current preliminary form show the effects of consumptive water use, soil chemistry, and groundwater chemistry. The scheme currently used in the model to transfer water between the aquifer and the stream may be physically unrealistic in that it is independent of aquifer properties and water level. Improvements which relate the stream-aquifer interaction to aquifer properties and water level (see Gelhar and Wilson, 1974) will be incorporated after the model has been tested over a long time frame in its current form. Baseflow recession and well drawdown data will be used to estimate the required aquifer parameters for the proposed model improvements.

The consumptive use estimates from the USBR EVPCOM program will require careful re-evaluation. The current results, which are based on the well established Jensen-Haise equation, are substantially higher than commonly accepted values for the area. Lysimeter data and results from current water-use studies will be used in this evaluation.

Generally the existing data base will provide adequate input for the long-term simulations beginning as much as 50 years ago. Even though approximate, these simulations can provide important insight on the long-term changes or irrigation return-flow quality. Data on groundwater quality and pumpage are very limited; no continuous long-term groundwater-quality records have been located, and systematic pumpage information is lacking. The current USGS study on groundwater resources of the valley may provide some data on pumpage which should be useful in testing the groundwater transfer in the models. The emphasis of our current sampling program is on groundwater quality. We are planning to maintain the same sampling network and improve the analysis procedures by using field analyses for some of the ions.

ACKNOWLEDGEMENTS

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REFERENCES

Basler, J. A. and L. J. Alary. 1968. Quality of the shallow water in the Rincon and Mesilla valleys, New Mexico and Texas. U. S. Geological Survey. Open file report.

Busch, F. E., and J. D. Hudson. Ground-water levels in New Mexico. Basic data report. New Mexico State Engineer, Sante Fe. 1964-1973 (yearly reports).

Conover, C. S. 1954. Groundwater conditions in the Rincon and Mesilla valleys and adjacent areas in New Mexico. U. S. Geological Survey. Water supply paper 1230.

Dutt, G. R., M. J. Shaffer, and M. J. Moore. 1972. Computer simulation model of dynamic bio-physico-chemical processes in soils. Technical bulletin 196. Department of Soils, Water and Engineering. University of Arizona, Tucson, Arizona.

Gelhar, L. W. and J. L. Wilson. 1974. Groundwater Quality Modeling. Groundwater, vol. 12, no. 6.

Gupta, S. K., K. K. Tanji, and J. N. Luthin. 1975. A three diminsional finite element groundwater model. Contribution 152. California Water Resources Center. University of California, Davis, California.

Hassan, A. A., D. C. Kleinecke, S. J. Johanson, and C. E. Pierchala. 1974. Mathematical modeling of water quality for water resources management. Two volumes. Research grant technical completion report to the office of Water Resources Research. U. S. Department of the Interior. Washington, D. C.

Henderson, D. C. and E. F. Sorensen. 1968. Consumptive irrigation requirements of selected irrigated areas in New Mexico. Bulletin 531. Agricultural Experiment Station. New Mexico State University, Las Cruces.

Hornsby, A. G. 1973. Prediction modeling for salinity control in irrigation return flows. National Environmental Research Center. U. S. Environmental Protection Agency. Corvallis, Oregon.

Jensen, M. E., D. C. N. Robb, and C. E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. J. Irrigation and Drain Division, American Society of Civil Engineering. 96, IRI, pp. 25-38.

King, L. G., and R. J. Hanks. 1973. Irrigation management for control of quality of irrigation return flow. Environmental Protection Technology Series. Report #EPA-R2-73-265. U. S. Environmental Protection Agency, Washington, D. C.

King, W. E., J. W. Hawley, A. M. Taylor, and R. P. Wilson. 1969. Hydrogeology of the Rio Grande Valley and adjacent intermontane areas of southern New Mexico. New Mexico Water Resources Research Institute report no. 6.

King, W. E., J. W. Hawley, A. M. Taylor, and R. P. Wilson. 1971. Geology and groundwater resources of central and western Dona Ana County, New Mexico. New Mexico Bureau of Mines and Mineral Resources. Report no. 1.

Konikow, L. F. and J. D. Bredehoeft. 1974. Modeling flow and chemical quality changes in an irrigated stream aquifer system. Water Resources Research. Vol. 8, pp. 546-562.

Lansford, R. R., et al. 1973. An analytical interdisciplinary evaluation of the utilization of the water resources of the Rio Grande in New Mexico. New Mexico Water Resources Research Institute report no. 20, 152 pp.

Lansford, R. R., et al. 1976. Demonstration of irrigation return flow salinity control in the upper Rio Grande. Annual report, year 1. New Mexico Water Resources Institute report no. 70, 102 pp.

Leggat, E. R., M. E. Lowery, and J. W. Hood. 1962. Groundwater resources of the lower Mesilla Valley, Texas and New Mexico. Texas Water Commission bulletin 6203.

Lyons, T. C. and J. Stewart. 1973. Groundwater model development and verification for the San Jacinto groundwater basin. Water Resources Engineers, Inc. Final report on task XVI(s)-1.

Maddaus, W. and M. A. Aaronson. 1972. A regional groundwater resource management model. Water Resources Research. Vol. 8, pp. 231-237.

Mercado, A. 1976. Nitrate and chloride pollution of aquifer, regional study with the aid of a single-cell model. Water Resources Research, in press.

Richardson, G. L. 1971. Water table investigation in the Mesilla Valley. M. S. thesis. New Mexico State University, Las Cruces.

Scofield, C. S. 1938. Quality of water of the Rio Grande basin above Fort Quitman, Texas. U. S. Geological Survey. Water supply paper 839.

Shaffer, M. J., R. W. Ribbens, and C. W. Huntley. 1975. Prediction of mineral quality of irrigation return flow, vol. V, detailed return flow salinity and nutrient simulation model. Draft prepared for Office of Research and Development, U. S. Environmental Protection Agency, Washington, D. C.

U. S. Bureau of Reclamation. 1974. Irrigation Management Services 1973 annual report. Rio Grande Project, New Mexico-Texas. Bureau of Reclamation, Denver, Colorado.

U. S. Bureau of Reclamation. 1975a. Prediction of mineral quality of irrigation return flow, vol. I. Bureau of Reclamation. Engineering and Research Center, Denver, Colorado. 58 pp.

U. S. Bureau of Reclamation. 1975b. Prediction of mineral quality of irrigation return flow, vol. III. Bureau of Reclamation. Engineering and Research Center, Denver, Colorado. 301 pp.

Walker, W. 1976. Assessment of irrigation return flow models. EPA report on a workshop held at Colorado State University March 19-21, 1975. In press.

Wilcox, L. V. 1968. Discharge and salt burden of the Rio Grande above Fort Quitman, Texas, and salt balance conditions on the Rio Grande project. Summary report for the 30-year period 1934-1963. U. S. Salinity Laboratory research report no. 113. Riverside, California.

A CONCEPTUAL HYDROSALINITY MODEL FOR PREDICTING SALT LOAD IN IRRIGATION RETURN FLOWS

Kenneth K. Tanji[1]

INTRODUCTION

Under the Federal Water Quality Pollution Control Act of 1972 and its Amendments (Federal Register, 1972), the U. S. Environmental Protection Agency has a statutory charge to control point-source discharges of pollutants, including agricultural runoff, to navigable waters, For irrigated agriculture, there is a need to identify both the level of management required to achieve pollution control goals and the kinds of data and information that are required to evaluate irrigation return flows. The dissolved mineral salt load in return flows from irrigated agriculture and its control are regarded as the major, if not the most important, water-quality problem in semiarid regions of the United States (for example, Ayers and Coppock, 1974) and elsewhere.

Comprehensive, dynamic hydrosalinity simulation models are being formulated and some of them have been applied to large-scale systems but most of them are not widely used for a variety of reasons, including the costs involved, requirement of an extensive input data base, and difficulties in verifying model outputs. For these and other reasons, the need is urgent for a "best-estimate methodology" using best available information and judgment.

Presented herein is a description and applications of a steady-state conceptual hydrosalinity model. The model may serve as a first-order approximation in lieu of more detailed and refined models for evaluating mass emission of salts from irrigated agriculture.

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MODELING PRINCIPLES AND OBJECTIVES

The analysis of the flow of water and salts in irrigated agriculture is admittedly very complex, usually requiring computer modeling and simulations (Hornsby, 1973), but such models are available for only a comparatively small number of river basins and irrigation projects. An interim solution using the "best-estimate methodology" is proposed.

It is presumed that mass emission of salts from irrigated lands could be controlled to a great extent with irrigation efficiencies that provide adequate water to meet the evapotranspiration needs of crops and salt control in crop root zones. This implies that the quantity of water used may be minimized with due allowances for attainable on-farm irrigation application efficiencies and project distribution efficiencies, salt control measures for the most sensitive crops grown in the area, current limitations on delivery and size of stream, and the capture of usable irrigation return flow.

The approach taken in the proposed model simplifies the "real-world" complexities to circumvent the constraint of the lack of a detailed field data base and to take advantage of the best available information and judgment. The time scale chosen is an irrigation season. This model is applicable to large tracts of land such as an irrigation project, and may not have the resolution for smaller-scale systems.

The conceptual model is based upon two major underlying principles: conservation of mass and steady state. Mass balance is invoked for both water and salts so that quantitative estimates could be made. Steady-state conditions are assumed to reflect long-term rather than short-term trends.

The hydrosalinity model focuses on the crop root-zone portion of the irrigated agriculture system. It attempts to consider only the main flow pathways of water and salts, with some considerations for sinks and sources and initial conditions. Input data requirements and model coefficients that are not readily available can be estimated from experience and judgment or translated from other similar projects, so that there will be no constraints placed on the application of the model to most areas.

This methodology has requisite characteristics to evaluate water management and practices, irrigation water quality, and soil properties that affect salt load in irrigation return flows. Its output could be used as input to other models dealing with stream, lake, and groundwater systems. It could be used to appraise not only the current and historical hydrologic and salinity conditions, but also to estimate anticipated changes in water and salt flows if certain management practices are modified.

DESCRIPTION OF THE IRRIGATION AGRICULTURE SYSTEM

The irrigated agriculture system is simplified to evaluate salt emission and controls without resorting to finely-tuned dynamic simulation models. It is possible that in generalizing this system, with a focus on the crop root zone, site-specific exceptions may arise. Such exceptions should be incorporated with pertinent modifications to the mathematical model described in detail in the Appendix.

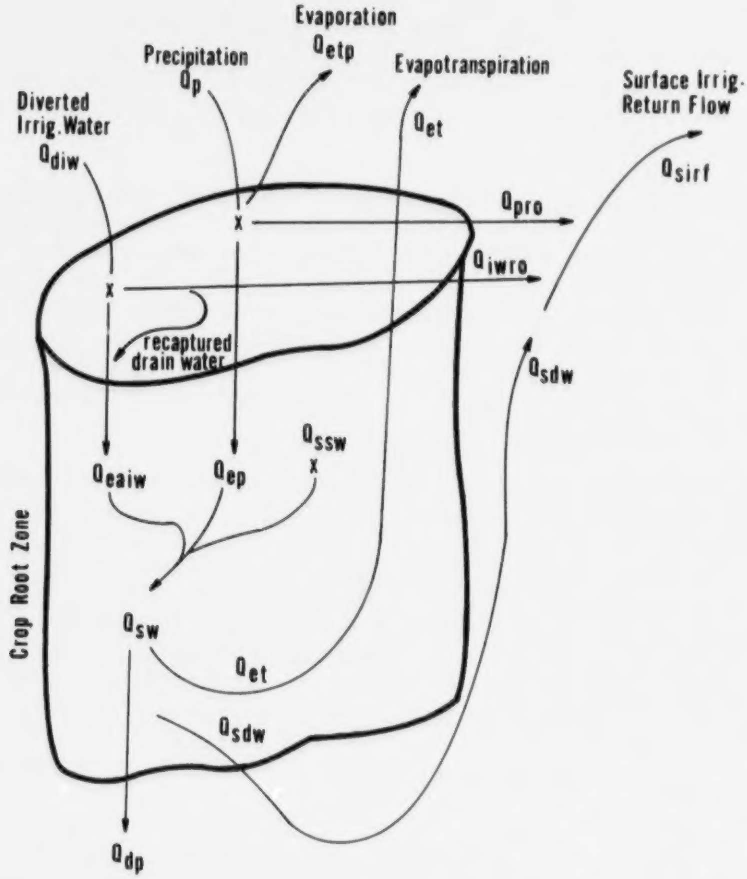
Evaporation
Q_{etp}
Precipitation
Q_p
Evapotranspiration
Q_{et}
Surface Irrig. Return Flow
Q_{sirf}
Diverted Irrig. Water
Q_{diw}
Q_{pro}
Q_{iwro}
recaptured drain water
Q_{sdw}
Q_{ssw}
Q_{eaiw}
Q_{ep}
Crop Root Zone
Q_{sw}
Q_{et}
Q_{sdw}
Q_{dp}

Figure 1. A conceptual view of water flow in the crop root zone portion of the system irrigated agriculture. The symbol Q refers to quantity of water. Definition of subscripts are given in the Appendix.

Figure 1 schematically gives the hydrologic inputs and outputs, and their flow pathways. The symbol Q denotes quantity of water (ha-m, ac-ft) obtained from the product of surface area (ha, ac) and unit water flow (ha-m/ha, ac-ft/ac) for the irrigation season. The inputs include precipitation (Q_p), and diverted irrigation water (Q_{diw}) from all sources during the irrigation season. Stored soil water (Q_{ssw}) from the nonirrigation season is a source. The outputs include evapotranspiration (Q_{et}, Q_{pet}), surface runoff (Q_{iwro}, Q_{pro}), deep percolation (Q_{dp}), and collected subsurface drainage (Q_{sdw}) from underdrains, interception by open drains, drainage wells, etc. The sum of Q_{sdw}, Q_{iwro}, and Q_{pro} is collectively referred to as surface irrigation return flow (Q_{sirf}). The mass inflow of water to the crop root zone is made up of effective applied irrigation (Q_{eaiw}), effective precipitation (Q_{ep}) and stored soil water (Q_{ssw}).

Figure 2 shows the corresponding salt inputs and outputs, and their flow pathways. The salinity parameter (C) used herein is total dissolved solids (TDS) in mg/liter. The mass (tonnes, tons) of dissolved salts (M) is the product of the salt concentration, the volume of water, and an appropriate conversion factor. Provisions have been made for salt pickup in surface runoffs (C_{iwrosp}, C_{prosp}). The TDS of soil water (C_{sw}) is the volume-weighted average of effective applied irrigation water, effective precipitation, and stored soil water.

The soil water (Q_{sw}) is subject to concentration in volume due to evapotranspiration losses. This degree of volume concentration is designated ETCF. In addition, provisions have been made to include the tendency of the applied water to pickup salts (M_{sp}) or to deposit salts (M_{sd}) as it is concentrated in the soil solution. This mineral dissolution-mineral precipitation phenomena is partly accounted for by the effects of irrigation water quality and leaching fraction (Rhoades et al., 1973). In addition, the contribution of dissolved salts by excess native soil gypsum when present is empirically considered. The final concentration of salts in the root zone after evapotranspiration and salt pickup-salt deposition is C'_{sw}.

It is assumed that the TDS of deep percolation and subsurface drainage is identical to C'_{sw}. The salt concentration in the surface irrigation return flow (C_{sirf}) is the volume-weighted average of collected subsurface and surface runoff components.

If steady-state conditions are assumed, there will be no change expected with time within the study period (irrigation season, hydrologic year, crop rotation period, etc.) in contrast to nonsteady-state or dynamic conditions. Also, if conservation of mass is invoked the outputs of water and salts will be balanced by the inputs and sources and sinks. Where irrigation is not practiced year-round and significant precipitation occurs between irrigation seasons, initial conditions such as stored soil water should be

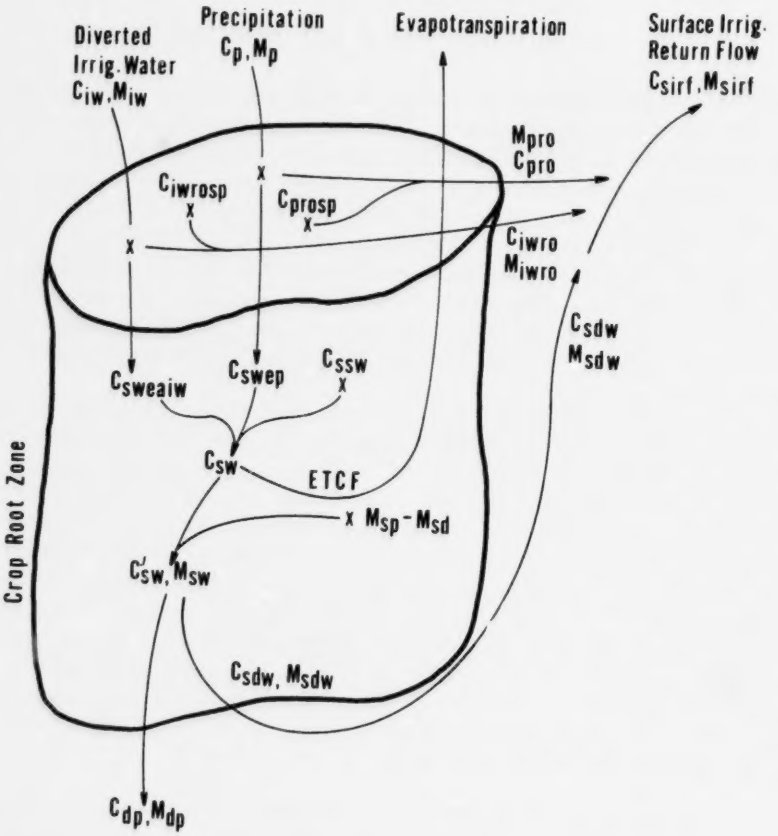
Diverted Irrig. Water
C_{iw}, M_{iw}
Precipitation
C_p, M_p
Evapotranspiration
Surface Irrig. Return Flow
C_{sirf}, M_{sirf}
M_{pro}
C_{pro}
C_{iwrosp}
C_{prosp}
C_{iwro}
M_{iwro}
C_{sdw}
M_{sdw}
C_{sweaiw}
C_{swep}
C_{ssw}
C_{sw}
ETCF
$M_{sp} - M_{sd}$
C'_{sw}, M_{sw}
C_{sdw}, M_{sdw}
Crop Root Zone
C_{dp}, M_{dp}

Figure 2. A conceptual view of salt flow in the crop root zone portion of the system irrigated agriculture. The symbols C and M respectively, denote concentration (TDS) and mass (tonnes) of salts. Definition of subscripts are found in the Appendix.

considered. However, if irrigation is practiced year-round, then it is assumed that stored soil water would be the same at the beginning and at the end of the study period, and it could be neglected.

This model does not consider rim inflows from contiguous areas. Such rim inflows may consist of both surface and subsurface origins, including surface runoff, interflow, rising groundwaters, etc. Water percolating past the root zone is split into two streams, subsurface drainage and deep percolation, which usually can only be guess-estimated in the absence of adequate hydrogeologic characterization. Space-averaging over the study area and time-averaging over the study period are necessary for all model parameters and coefficients.

MODEL CALIBRATION AND VERIFICATION

To obtain credibility the model should be first calibrated with present and/or historical data. In this particular case, the calibration procedure involved the fitting of calculated flow (volume) and TDS of surface irrigation return flows from Glenn-Colusa Irrigation District (GCID) with measured data from the 1973 irrigation season. This was then followed by verification which involved predicting present and/or historical data other than the one used for calibration, for example, the 1970 irrigation season. A comparison between predicted and measured results in the verification step gives some estimate of the validity of the model for that particular system.

Figure 3 gives the general location map where this model was applied in California. Figure 4 is a map of the 66,298 ha Glenn-Colusa Irrigation District which obtains its supply water by diverting Sacramento River water near Hamilton City and from Stony Creek. The main supply distribution canal runs along the district's western boundary. Surface irrigation return flows are conveyed in 11 lateral drains and collected in the Colusa Basin Drain. Flooded rice is the major crop in GCID, occupying 66 and 71% of the total irrigated acreage in 1973 and 1970, respectively. This district captured drain water equal to 23 and 29%, respectively of the total diversions in 1973 and 1970. The climate is of the Mediterranean type with a mean annual precipitation of 0.44 m. The irrigation season starts in April and ends in October.

Table 1 lists the required input parameters and coefficients for the conceptual model. The details of the computational procedure are given in the Appendix. The major sources of information were GCID'S Annual Report (1974) on Water Measurement Program for 1973, the California Department of Water Resources bulletin on Vegetative Water Use (1967, 1975) and our own water quality survey (Low et al., 1974) in this district.

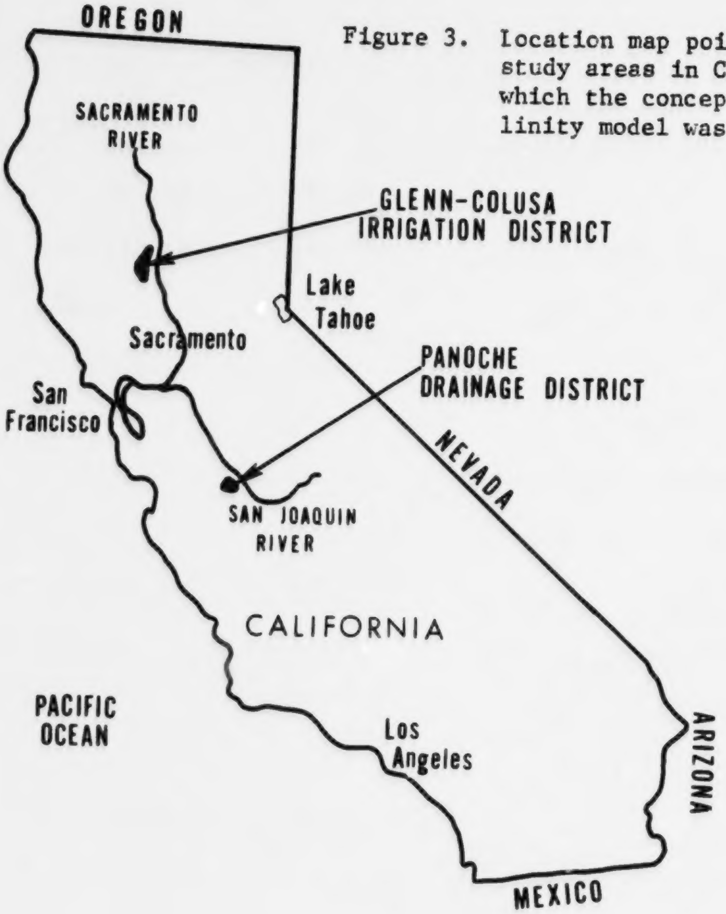
OREGON
SACRAMENTO RIVER
GLENN-COLUSA IRRIGATION DISTRICT
Lake Tahoe
Sacramento
PANOCHE DRAINAGE DISTRICT
San Francisco
NEVADA
SAN JOAQUIN RIVER
CALIFORNIA
PACIFIC OCEAN
Los Angeles
ARIZONA
MEXICO

Figure 3. Location map pointing out two study areas in California to which the conceptual hydrosalinity model was applied.

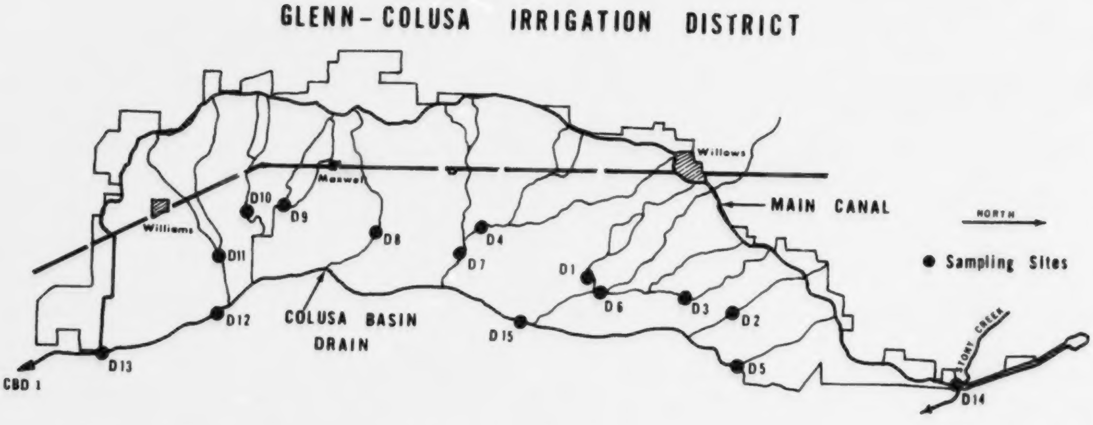
GLENN-COLUSA IRRIGATION DISTRICT
Willows
Maxwell
Williams
MAIN CANAL
NORTH
● Sampling Sites
D1
D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
D13
D14
D15
COLUSA BASIN DRAIN
STONY CREEK
CBD 1

Figure 4. Map of the 66,400 ha Glenn-Colusa Irrigation District in the Sacramento Valley.

Table 1. Required Input Data and Model Coefficients*

Parameters and Coefficients	Calibration 1973 GCID	Verification 1970 GCID	Application 1975 PDD
Total Land Area (A), ha	66,298	66,298	17,724
Diverted Irrigation Water (Q_{diw}), ha-m	99,059	92,389	18,076
Irrigation Application Efficiency, (E_{iae})	0.80	0.80	0.75
Precipitation (Q_p), ha-m	3,095	1,850	2,698
Precipitation Runoff Coefficient (a)	0.2	0.2	0.2
Precipitation Evapotranspiration Coefficient(b)	0.7	0.7	0.7
Effective Precipitation Coefficient (c)	0.1	0.1	0.1
Stored soil Water (Q_{ssw}), ha-m+	1,486	8,318	--
Water Holding Capacity of Soil (D_{whc}), m/m	0.09	0.09	--
Average Rooting Depth (D_r), m	0.76	0.76	--
Stored Soil Water Coefficient (d)	1.0	0.56	--
Evapotranspiration (Q_{et}), ha-m	6,104	6,104	--
Potential Evapotranspiration (Q_{pet}), ha-m/ha	1.02	1.02	1.25
Evapotranspiration Coefficient (e)	0.9	0.9	0.4
Deep Percolation Coefficient (f)	0.8	0.8	0.7
TDS of Diverted Water (C_{iw}), mg/ℓ	91	99	234
Salt Pickup by Runoff (C_{iwrosp}), mg/ℓ	5	5	35
TDS of Precipitation (C_p), mg/ℓ	10	10	10
Salt Pickup by Runoff (C_{prosp}), mg/ℓ	5	5	35
Salt Pickup-Salt Deposition ($M_{sp}-M_{sd}$), tonnes	121,777	102,471	58,824
Gypsum Contribution, tonnes/ha-m water	0	0	21.48

* Numerical values given are for model calibration and verification for Glenn-Colusa Irrigation District using the 1973 and 1970 irrigation season, and application to Panoche Drainage District for the 1975 calendar year.

+ Not required, but given for informational purposes.

The numerical data given for the required input data and coefficients are the final ones used for calibration for the 1973 irrigation season. This calibration was obtained with three iterations in attempting to fit the calculated flow and TDS of surface irrigation return flows to that of monitored values. The only two coefficients which were adjusted in the calibration process were the deep percolation coefficient (f) and the irrigation application efficiency (E_{iae}).

Table 2 gives the results of the final calibration run. It was possible to obtain outputs on irrigation return flow that were within ±2% of the observed data.

The calibrated model was then applied to the 1970 irrigation season for model verification. Table 1 contains the required input parameters for 1970. The only input data different in 1970 are diverted water, precipitation during growing season, stored soil water from winter nonirrigation season, and TDS of supply water (GCID, 1971). All other model parameters and coefficients were identical to the calibration run. Figure 5 gives a plot of salt pickup-salt deposition as related to leaching fraction. The data points for Feather River water came from van Schilfgaarde et al. (1974), based on consumptive use of 0.91 m/yr. The other two curves are, at best, estimates for the Sacramento River water (supply water for GCID) and the Delta-Mendota Canal water (supply water for Panoche Drainage District). All three waters have a negative saturation index (Langelier, 1936), which indicates that these waters have a tendency to dissolve calcium carbonate upon contact.

Table 2 reports the results of model verification. It appears that the model can only predict to within ±33% of observed values. These results, however, are acceptable, considering the simplifying assumption made in the model and the fact that 1970 was a normal year (0.461 m precipitation from November, 1969 through October, 1970) as compared to 1973 (0.677). Table 3 contains a partial listing of various outputs from the 1973 calibration and 1970 verification runs.

MODEL APPLICATION

The calibrated and verified model was applied to a second irrigation project to further test the utility of this approach and to consider an area containing salt-affected soils (Figs. 3 and 6). The Panoche Drainage District (PDD), comprising of four irrigation districts, is located in the San Joaquin Valley and obtains its supply water from two imported sources: Delta-Mendota Canal and the California Aqueduct. The drain waters from the 17,724 ha PDD are collected in several canals and discharged into the Panoche Drain (Station I-6

Table 2. Results of Model Calibration and Verification on Glenn-Colusa Irrigation District for the 1973 and 1970 Irrigation Season (April-October) respectively.

Parameter	Measured	Calculated	Difference
Calibration (1973)			
Surface Irrigation Return Flow, ha-m	26,583	27,112	+2.0%
TDS of Return Flow, mg/ℓ	220	215	-2.3%
Salt Mass in Return Flow, tonnes	58,522	58,328	-0.3%
Verification (1970)			
Surface Irrigation Return Flow, ha-m	34,512	23,127	-33.0%
TDS of Return Flow, mg/ℓ	192	236	+22.9%
Salt Mass in Return Flow, tonnes	66,305	54,614	-17.6%

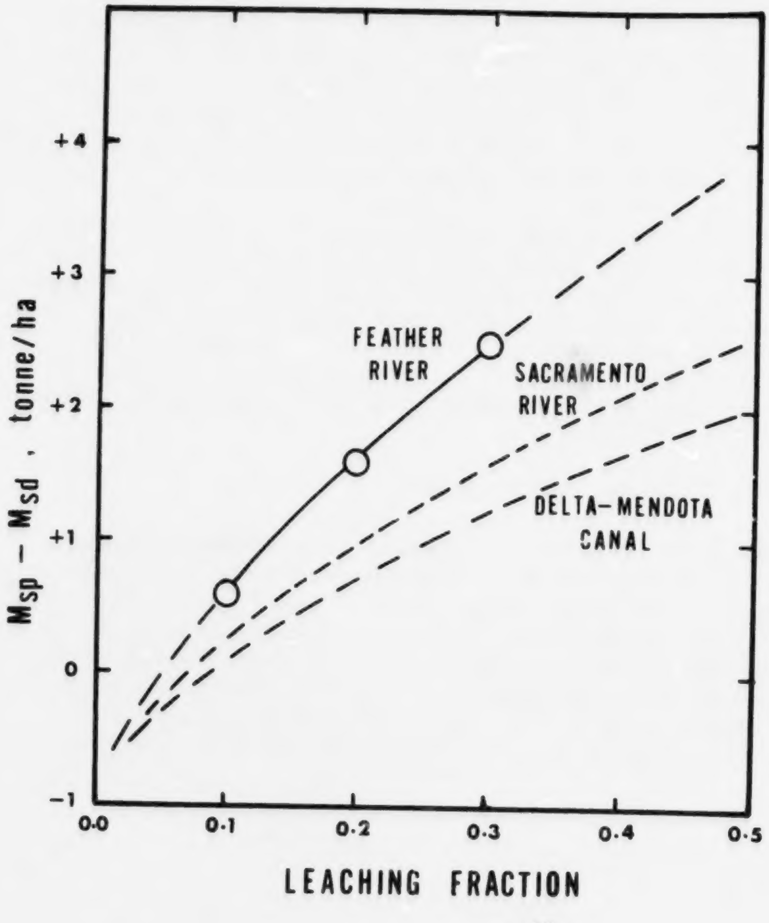

Figure 5.

Relations between salt pickup-salt deposition from applied irrigation waters and leaching fraction.

Table 3. Partial Summary of Calibration and Verification Outputs for Glenn-Colusa Irrigation District for the 1973 and 1970 Irrigation Seasons, Respectively

Parameter	1973	1970
Diverted Irrigation Water, ha-m/ha	1.49	1.39
Irrigation Application Efficiency	0.80	0.80
Irrigation Efficiency	0.53	0.60
Leaching Fraction	0.35	0.26
Leaching Beyond Root Zone, ha-m/ha	0.50	0.32
Deep Percolation, ha-m/ha	0.40	0.26
Subsurface Drainage, ha-m/ha	0.10	0.06
Irrigation Runoff, ha-m/ha	0.30	0.28
Precipitation Runoff, ha-m/ha	0.01	0.006
Surface Irrigation Return Flow, ha-m/ha	0.41	0.35
ET Concentration Factor of Soil Water	2.83	3.85
TDS of Soil Water after ET, mg/ℓ	221	346
Salt Pickup-Salt Deposition, tonnes/ha	1.84	0.63
Final TDS of Soil Water, mg/ℓ	585	825
TDS of Surface Irrigation Return Flow, mg/ℓ	215	236

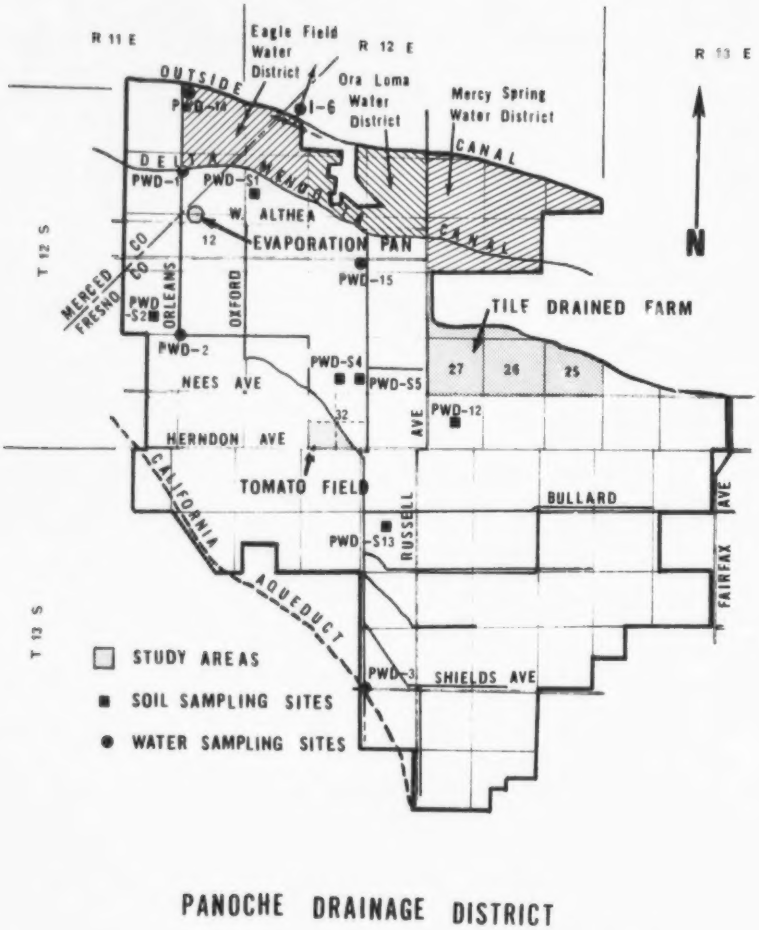
R 11 E
Eagle Field Water District
R 12 E
Ora Loma Water District
Mercy Spring Water District
R 13 E
OUTSIDE
PWD-14
I-6
CANAL
DELTA MENDOTA CANAL
PWD-1
PWD-S1
W. ALTHEA
EVAPORATION PAN
12
N
T 12 S
MERCED CO.
FRESNO CO.
PWD-15
PWD -S2
ORLEANS
OXFORD
TILE DRAINED FARM
PWD-2
PWD-S4
NEES AVE
PWD-S5
27
26
25
32
AVE
PWD-12
HERNDON AVE
CALIFORNIA
TOMATO FIELD
BULLARD
RUSSELL
PWD-S13
AVE
FAIRFAX
AQUEDUCT
T 13 S
▢ STUDY AREAS
■ SOIL SAMPLING SITES
● WATER SAMPLING SITES
PWD-3
SHIELDS AVE
PANOCHE DRAINAGE DISTRICT

Figure 6. Map of the 17,800 ha Panoche Drainage District in the San Joaquin Valley.

in Fig. 6) for reuse by the Grasslands Water District, an irrigated pasture-waterfowl habitat entity. The major crops grown in the PDD are tomato, cotton, and winter barley. The first two crops mentioned are furrow-irrigated. Unlike GCID, the irrigation season in PDD encompassed the calendar year, January through December, 1975.

Table 1 contains the input data and coefficients for PDD. In addiion to those sources of information and data listed for GCID, other data was obtained from an ongoing investigation (Tanji et al., 1976) in PDD. Stored soil water was not considered in the calculations. The mean annual precipitation in this area is about 0.15 m/yr.

Table 4 contains the results of application of this model to PDD. The model predicted flow of surface irrigation return flows to within +17% of monitored value. However, the TDS and salt load were greatly under predicted by using only $M_{sp}-M_{sd}$ in Fig. 4. It is concluded that the presence of native soil gypsum (Table 5) contributed substantially to the dissolved salt load. When it was assumed that the solubility of gypsum in the soil solution is 25 meq/liter, or 21.49 tonnes/ha-m, the calculated results for TDS and the mass of salts in the surface irrigation return flows were -7% and +9%, respectively, of measured values. A further verification of model outputs is the agreement between the calculated 7,146 mg/liter TDS of the soil solution (C'_{sw}) with the measured 6,710-8,900 mg/liter of TDS of tile drainage effluents from the 678 ha tile-drained farm (Fig. 6).

It appears that this steady-state conceptual model has practical utility. How well this model compares with more finely-tuned dynamic models is not known. Although the state-of-the-art of computer modeling has been advanced significantly, the evaluation of soil-salt interactions and predictions on mass emission of salts is usually less than desirable (Biggar and Tanji, 1976).

The final step taken with this model was to project flow, TDS, and salt load in PDD assuming that salt control practices resulted in a hypothetical 20% reduction in diverted water. Table 6 gives the probable effects, where TDS is increased by 6%, return flow decreased by 13%, and salt load decreased by 22%. Due to the presence of gypsum in the soil, TDS is not significantly affected. If gypsum was absent, the percent increase in TDS would be much greater.

Other computed results are given in Table 6, and these may be compared to not only the 1975 PDD study period but also to GCID, Table 3.

Table 4. Results of Model Applied to the Panoche Drainage District for the Calendar Year 1975.

	Measured		Calculated	
Parameter	Measured	No Gypsum	With Gypsum	Difference
Surface Irrigation Return Flow, ha-m	5,585	6,552	--	+17.3%
TDS of Return Flow, mg/ℓ	1,955	458	1,818	-7.0%
Salt Mass in Return Flow, tonnes	109,267	30,027	119,191	+9.1%

Table 5. Soil Data from Panoche Water District *

Depth (m)	EC_e (mmhos/cm)	Estimated Soluble Salts (tonnes/ha-m soil)	Gypsum (tonnes/ha-m soil)	Boron (mg/ℓ)
0.0 -0.15	1.60	7.95	2.86	0.99
0.15-0.3	1.51	7.80	2.79	1.15
0.3 -0.45	1.73	9.79	3.24	1.48
0.45-0.6	2.05	11.11	4.00	2.05
0.6 -0.9	2.80	16.06	4.90	2.80
0.9 -1.2	3.61	20.96	28.34	3.53
1.2 -1.5	3.96	23.22	19.60	3.57
1.5 -1.8	4.17	24.35	38.37	3.50
1.8 -2.1	3.78	22.81	37.46	3.16
2.1 -2.4	4.04	30.91	150.01	3.27
2.4 -2.7	3.64	26.16	107.64	3.83
2.7 -3.0	1.02	4.45	3.02	1.90

* Average of 13 sampling sites to perched water table.

Table 6. Partial Summary of 1975 and Hypothetical Assumed Level of Achieving Salt Control in Panoche Drainage District

Parameter	1975	Assumed Level	% Difference
Diverted Irrigation Water, ha-m/ha	1.02	0.81	-20
Irrigation Application Efficiency	0.75	0.75	---
Irrigation Efficiency	0.45	0.56	---
Leaching Fraction	0.36	0.20	---
Leaching Beyond Root Zone, ha-m/ha	0.28	0.13	-54
Deep Percolation, ha-m/ha	0.20	0.09	-55
Subsurface Drainage, ha-m/ha	0.08	0.04	-50
Irrigation Runoff, ha-m/ha	0.26	0.20	-23
Precipitation Runoff, ha-m/ha	0.03	0.03	---
Surface Irrigation Return Flow, ha-m/ha	0.37	0.27	-27
TDS of Supply Water	234	234	---
ET Concentration Factor of Soil Water	2.78	4.90	---
TDS of Soil Water after ET, mg/ℓ	639	1,120	+75
Salt Pickup-Salt Deposition, tonnes/ha	1.52	0.79	-54
Gypsum Contribution, tonnes/ha	16.76	13.47	---
Final TDS of Soil Water, mg/ℓ	7,146	12,196	+71
TDS of Surface Irrigation Return Flow, mg/ℓ	1,818	1,921	+6
Surface Irrigation Return Flow, ha-m	5,552	4,835	-13
Mass of Salts in Surface Return Flow, tonnes	119,191	92,932	-22

Q_{ssw} = Stored Soil Water

d = Stored Soil Water Coefficient

D_{whc} = Unit Water Holding Capacity

D_r = Rooting Depth

A = Land Area

Q_{et} = Evapotranspiration

e = ET Coefficient

Q_{pet} = Potential Evapotranspiration

Q_{dp} = Deep Percolation

f = Deep Percolation Coefficient

Q_{sdw} = Subsurface Drainage Water

Q_{sirf} = Surface Irrigation Return Flow

E_{ie} = Irrigation Efficiency

LF = Leaching Fraction

M_i = Salt Input

M_o = Salt Output

C_{iw} = TDS of Diverted Irrigation Water

M_{diw} = Salt Mass in Diverted Irrigation Water

SMCF = Salt Mass Conversion Factor

C_{iwrosp} = Salt Pickup by Tailwater

C_{iwro} = TDS of Tailwater

M_{iwro} = Salt Mass in Tailwater

C_p = TDS of Precipitation

M_p = Salt Mass in Precipitation

C_{prosp} = Salt Pickup by Precipitation Runoff

C_{pro} = TDS of Precipitation Runoff

M_{pro} = Salt Mass in Precipitation Runoff

ETCF = ET Concentration Factor

C_{sweaiw} = TDS of Q_{eaiw} after ET

C_{swep} = TDS of Q_{ep} after ET

C_{ssw} = TDS of Q_{ssw} after ET

Q_{sweaiw} = Q_{eaiw} after ET

Q_{swep} = Q_{ep} after ET

Q_{sssw} = Q_{ssw} after ET

C_{sw} = TDS of Soil Water after ET

$(M_{sp} - M_{sd})$ = Salt Pickup-Salt Deposition

G_{sp} = Dissolved Gypsum

C'_{sw} = TDS of Soil Water after ET, $(M_{sp} - M_{sd})$, and G_{sp}

M_{sw} = Salt Mass in Soil Water

C_{dp}, C_{sdw} = TDS of Deep Percolation and Subsurface Drainage

M_{dp}, M_{sdw} = Salt Mass in Deep Percolation and Subsurface Drainage

C_{sirf} = TDS of Surface Return Flow

M_{sirf} = Salt Mass in Surface Return Flow

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LITERATURE CITED

Ayers, R. and R. Coppock. 1974. Salt management: California's most complex water quality problem. Univ. of Calif., Div. of Agr. Sci., Environmental Concerns, 19 pp.

Biggar, J. W. and K. K. Tanji. 1976. Soil-salt interactions in relation to salt control. Trans. Amer. Soc. Agr. Eng. (in press).

California Department of Water Resources. 1967. Vegetative water use. Bull. No. 113-2, 82 pp.

California Department of Water Resources. 1975. Vegetative water use, 1974. Bull. No. 113-3, 104 pp.

Federal Register. 1972. National pollutant discharge elimination system. Environmental Protection Agency. Fed. Reg. 37 (234): 25898-25906, December 5.

Glenn-Colusa Irrigation District. 1971. Water measurement program for 1970. 17 pp. + 28 Tables + 29 Figures and Map.

Glenn-Colusa Irrigation District. 1974. Water measurement program for 1973. 4 pp. + 31 Tables + 26 figures and Maps.

Hornsby, A. G. 1973. Prediction modeling for salinity control in irrigation return flows. U. S. Environmental Protection Agency, Environmental Protection Technical Series, EPA-R2-73-168, 55 pp.

Langelier, W. F. 1936. The analytical control of anticorrosion water treatment. J. Amer. Water Works Assoc., 28:1500-1521.

Low, W. H., K. K. Tanji and A. F. Quek. 1974. Return flow water quality appraisal, Glenn-Colusa Irrigation District, calendar year 1973. I: Water balance, salinity, and suspended matter. Univ. of Calif., Dept of Water Sci. and Eng. Paper 4007, 23 pp.

Rhoades, J. D., R. D. Ingvalson, J. M. Tucker, and M. Clark. 1973. Salts in irrigation drainage waters: I. Effects of irrigation water composition, leaching fraction, and time of year on the salt compositions of irrigation drainage waters. Soil Sci. Soc. Amer. Proc. 37:770-774.

Tanji, K. K., J. W. Biggar, G. L. Horner, R. J. Miller, W. O. Pruitt et al. 1976. 1975-76 Annual Report to the U. S. Environmental Protection Agency on EPA Grant No. R 803603-01-1, Irrigation tailwater management. Univ. of Calif., Dept of Land, Air and Water Resources, Water Sci. and Eng. Paper 4011, 200 pp.

van Schilfgaarde, J., L. Bernstein, J. D. Rhoades and S. L. Rawlins. 1974. Irrigation management for salt control. J. Irrig. and Drainage Div., ASCE 100(IR3):321-338.

APPENDIX

HYDROLOGIC SUBMODEL

Hydrologic Inputs and Outputs

(1) $Q_i = Q_{diw} + Q_p + Q_{ssw}$

(2) $Q_o = Q_{iwro} + Q_{pro} + Q_{et} + Q_{dp} + Q_{sdw}$

Diverted Irrigation Water

(3) $Q_{diw} = Q_{eaiw} + Q_{iwro}$

(4) $Q_{eaiw} = Q_{diw} (E_{iae})$

(5) $Q_{iwro} = Q_{diw} (1-E_{iae})$

Precipitation

(6) $Q_p = Q_{pro} + Q_{etp} + Q_{ep}$

(7) $Q_{pro} = a\ Q_p$

(8) $Q_{etp} = b\ Q_p$

(9) $Q_{ep} = c\ Q_p$

Water Inflow to Root Zone

(10) $Q_{sw} = Q_{eaiw} + Q_{ep} + Q_{ssw}$

(11) $Q_{ssw} = d\ (D_{whc})(D_r)(A)$

Water Outflow from Root Zone

(12) $Q_{sw} = Q_{et} + Q_{dp} + Q_{sdw}$

(13) $Q_{et} = e\ (D_{pet})(A)$

(14) $Q_{dp} = f\ (Q_{sw} - Q_{et})$

(15) $Q_{sdw} = (1 - f)(Q_{sw} - Q_{et})$

Surface Return Flow

(16) $Q_{sirf} = Q_{iwro} + Q_{pro} + Q_{sdw}$

Irrigation Efficiency and Leaching Fraction

(17) $E_{ie} = [Q_{sw} - (Q_{sirf} + Q_{dp})]/Q_{sw}$

(18) $LF = (Q_{sw} - Q_{et})/Q_{sw}$

SALINITY SUBMODEL

Salt Inputs and Outputs

(19) $M_i = M_{diw} + M_p + M_{ssw} + M_{sp}$

(20) $M_o = M_{iwro} + M_{pro} + M_{dp} + M_{sdw} + M_{sd}$

Diverted Irrigation Water

(21) $M_{diw} = (C_{iw})(Q_{diw})(SMCF)$

(22) $C_{iwro} = C_{iw} + C_{iwrosp}$

(23) $M_{iwro} = (C_{iwro})(Q_{diw})(SMCF)$

Precipitation

(24) $M_p = (C_p)(Q_p)(SMCF)$

(25) $C_{pro} = C_p + C_{prosp}$

(26) $M_{pro} = (C_{pro})(Q_{pro})(SMCF)$

ET Concentration Factor

(27) $ETCF = Q_{sw}/(Q_{sw} - Q_{et})$

Soil Water After ET

(28) $C_{sweaiw} = C_{iw}\ (ETCF)$

(29) $C_{swep} = C_p\ (ETCF)$

(30) $C_{ssw} = C_p(ETCF)$ or $C_{iw}\ (ETCF)$

(31) $Q_{sweaiw} = (Q_{eaiw}/Q_{sw})(Q_{sw} - Q_{et})$

(32) $Q_{swep} = (Q_{ep}/Q_{sw})(Q_{sw} - Q_{et})$

(33) $Q_{sssw} = (Q_{ssw}/Q_{sw})(Q_{sw} - Q_{et})$

(34) $C_{sw} = [(C_{sweaiw})(Q_{sweaiw}) + (C_{swep})(Q_{swep}) + (C_{ssw})(Q_{sssw})]/(Q_{sw} - Q_{et})$

Salt Pickup-Salt Deposition

(35) $(M_{sp} - M_{sd})$, obtained from Figure 5

Soil Water After ET and Salt Pickup-Salt Deposition

(36) $M_{sw} = (C_{sw})(Q_{sw} - Q_{et})(SMCF) + (M_{sp} - M_{sd}) + (G_{sp})$

(37) $C'_{sw} = M_{sw}/[(Q_{sw} - Q_{et})SMCF]$

Deep Percolation and Subsurface Drainage

(38) $C'_{sw} = C_{dp} = C_{sdw}$

(39) $M_{dp} = (C_{dp})(Q_{dp})(SMCF)$

(40) $M_{sdw} = (C_{sdw})(Q_{sdw})(SMCF)$

Surface Irrigation Return Flow

(41) $C_{sirf} = [(C_{iwro})(Q_{iwro}) + (C_{pro})(Q_{pro}) + (C_{sdw})(Q_{sdw})]/(Q_{iwro} + Q_{pro} + Q_{sdw})$

(42) $M_{sirf} = (C_{sirf})(Q_{sirf})(SMCF)$

DEFINITIONS OF SYMBOLS

Q_i = Hydrologic Input

Q_o = Hydrologic Output

Q_{diw} = Diverted Irrigation Water

E_{iae} = Irrigation Application Efficiency

Q_{eaiw} = Effective Applied Irrigation Water

Q_{iwro} = Irrigation Water Runoff

Q_p = Precipitation

Q_{pro} = Precipitation Runoff

Q_{etp} = ET of Precipitation

Q_{ep} = Effective Precipitation

a = Precipitation Runoff Coefficient

b = Precipitation ET Coefficient

c = Effective Precipitation Coefficient

Q_{sw} = Soil Water

INTEGRATING DESALINATION AND AGRICULTURAL SALINITY CONTROL TECHNOLOGIES

Wynn R. Walker 1/

INTRODUCTION

One of the most important requirements in developing regional salinity control strategies is the evaluation of alternatives for improving the quality of irrigation return flows. Two principal factors contribute to salinity in return flows: (1) leaching of salts applied in irrigation water but concentrated by evapotranspiration; and (2) pickup or loading of salts dissolved from subsurface soil and aquifer materials. Salinity control, therefore, generally focuses on either or both of these processes.

The most effective means of improving irrigation return flow quality begins with field data collection and modeling analyses to identify the complex hydro-chemical processes. These results are then combined with the costs or benefits of managing a particular process to formulate a salinity control "cost-effectiveness" relationship. A systematic comparison or integration of similar functions for other individual salinity control alternatives forms a policy for implementing the most effective improvements.

It appears that most of the salinity control emphasis on a regional basis is being given to minimizing salt pickup through institutional and structural programs aimed at reducing conveyance seepage and deep percolation from over-irrigation. Other possibilities include intercepting and disposing of return flows or removing the salts by desalination. Since the structure of salinity control strategies depends on the respective cost-effectiveness functions, the optimal policy may include a single measure or a combination of alternatives. The analytical procedures for accomplishing this comparative evaluation can be formulated as a series of multilevel optimizations. To demonstrate the general modeling concepts, this paper will center on a case study involving the integration of desalination and agricultural salinity control alternatives in the Grand Valley of western Colorado. This area is significant in the Colorado River Basin salinity problems and local solutions are complex. In order to simplify the presentation, the desalting and agricultural salinity control alternatives will be limited to reverse osmosis desalination and to concrete canal, lateral, and field ditch linings, respectively.

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DESALINATION COST MODEL

In the context of salinity control, desalting costs can be expressed in dollars per unit volume of salt extracted in order to compare the feasibility of desalination with other salinity control measures. A desalting system includes facilities for supplying raw water to the desalting plant itself and facilities to convey and dispose of the brine. Because the use of desalination depends upon its comparative economic feasibility, a substantial research effort has been made to develop cost predicting capabilities at the planning level. Prehen et al. (1970) summarized most of this information into a desalting cost calculating procedure for several alternative desalting methods and related facilities. This work was subsequently improved and expanded by the Bureau of Reclamation (U. S. Department of the Interior, 1972). The costing procedures outlined in these two publications were mathematically simulated and programmed for use on a digital computer. Seven types of desalting processes have been modeled:

(1) multi-stage flash distillation (MSF);
(2) vertical tube evaporation - multi-stage flash distillation (VTE-MSF);
(3) vapor compression - vertical tube evaporation - multi-stage flash distillation (VC-VTE-MSF);
(4) electrodialysis (ED);
(5) reverse osmosis (RO);
(6) vapor compression - vacuum freezing (VC-VF); and
(7) ion exchange (IX).

As an illustration, the reverse osmosis plant model is given in Table 1, using English units.

The model divides the cost into those expended during construction and those incurred annually in operating and maintaining the systems. Construction costs are amortized over the expected useful life of the facilities so that the costs in terms of water or salt are the sums of annual and amortized construction costs divided by the units of treated water or extracted salt. Construction costs are subdivided into eight categories as described below:

(1) Construction costs, including design, labor, and materials;
(2) Steam generating equipment (if utilized in a desalting process);
(3) Site development costs to provide offices, shops, laboratories, storage rooms, etc., and to improve the landscape encompassing the site, such as parking, grading, and fencing;
(4) Interest during construction, repaying borrowing costs, or money needed to finance the construction;
(5) Start-up costs necessary to test the system operation,

Table 1. Summary of cost functions for RO desalting plants

COST DESCRIPTION	COST FUNCTIONS	Remarks
Capital Costs, $ Million		
1. Construction Costs, C_1	C_1=(ENR/952.)*.473*X_t^.91	$X_t \geq 8$
	C_1=(ENR/952.)*.522*X_t^[illegible]	$4 \leq X_t \leq 8$
	C_1=(ENR/952.)*.575*X_t^[illegible]	$X_t \leq 4$
2. Steam Facilities, C_2	C_2=0.0	$X_t=C_p*\frac{(100.+1.7(77.-T))}{100.}$
3. Site Development, C_3	C_3=(ENR/952.)*0.1*C_p^[illegible]	
4. Interest During Construction, C_4	C_4=(C_1+C_3)*I_r/24.*8.*C_p^[illegible]	
5. Start-up Costs, C_5	C_5=(C_9+C_{10}+C_{13})/12,000.	
6. Owners' General Expense, C_6	C_6=.119(C_1+C_3)^[illegible]	
7. Land Costs, C_7	C_7=L_p(.5+.298*C_p)	
8. Working Capital, C_8	C_8=2.0*C_5	
Annual Costs, $ Thousands		
9. Labor & Materials, C_9	C_9=(BLS_1/3.76)*25.5*C_p^[illegible]	$C_p \geq 1.5$
	C_9=(BLS_1/3.76)*26.5*C_p^[illegible]	$C_p \leq 1.5$
10. Chemicals, C_{10}	C_{10}=(BLS_2/104.4)*18.25*U_f*C_p	
11. Fuel Costs, C_{11}	C_{11}=0.0	
12. Steam, C_{12}	C_{12}=0.0	
13 Electricity, C_{13}	C_{13}=E_c*3.65*C_p*U_f	
14. Replacement, C_{14}	C_{14}=36.5*U_f*C_p	

Description of symbols:

BLS_1 = Bureau of Labor Statistics cost index for labor
BLS_2 = Bureau of Labor Statistics cost index for chemicals
C_p = product water capacity, mgd
E_c = Electrical rates, $/1000 kwh
ENR = ENR Construction Cost Index
I_r = interest rate
L_p = land costs, $ million/acre
T = feedwater temperature, °F
U_f = plant use factor

train operating personnel, and establish operating criteria;
(6) Owners' general expenses for indirect costs such as project investigation, land acquisition, contract negotiation and administration, and other overhead expenses;
(7) Land costs for the site; and
(8) Working capital to cover daily expenses involved in plant operation.

In order to update the cost estimates on a year by year basis the costs are multiplied by the ratio of the ENR Construction Cost Index at the present time to the value of the index for July, 1971. The ENR Construction Cost Index is published regularly in Engineering News Record by McGraw-Hill, Inc.

The amortization of the construction costs is divided according to whether or not the costs represent depreciating capital. Depreciating capital costs (item 1-6 above) are multiplied by a "fixed charge factor" which is the percentage of total depreciating capital cost that is encompassed by interest, amortization insurance, taxes, and replacement. Non-depreciating capital costs (7 and 8) are multiplied by the interest rate selected for project evaluation or incurred in borrowing.

Annual operation and maintenance costs have been delineated into six categories described as:

(1) Labor and materials for plant operation;
(2) Chemicals for pretreatment and process additions;
(3) Fuel to power certain components in steam production;
(4) Electrical power for pumps, filters, etc;
(5) Steam generation operation and maintenance; and
(6) Replacement of process elements.

The construction and operational costs associated with feedwater supply, cooling (where necessary), and brine disposal are estimated by the same costing procedure described above. Feedwater is assumed to be supplied by either surface diversion or groundwater wells and then conveyed to the desalting plant through a concrete pipeline. Salts isolated in the brine flows may be disposed of in either evaporation ponds or injection wells, and again are assumed to be conveyed to the disposal site through a pipeline. Inflational updating is achieved through four additional cost indexes:

(1) USBR Pump and Prime Mover Cost Index;
(2) USBR Pumping Plant Cost Index;
(3) USBR Canal and Earthwork Cost Index; and
(4) USBR Concrete Pipeline Cost Index.

The eight construction cost categories for both plant and peripheral facilities are totaled in each category to determine an aggregate cost ($C_1' - C_{16}'$).

The costs of produced water and salt are then computed by:

$$C_{pw} = \frac{FCR \sum_{i=1}^{6} C_i' + I_r \sum_{i=7}^{8} C_i' + \sum_{i=9}^{14} C_i'}{C_p \times U_f \times 1.3818 \times 10^6} \qquad (1)$$

where C_{pw} = cost of product water in \$/m^3;
FCR = fixed charge rate;
I_r = interest rate;
C_p = product water capacity, m^3/day;
U_f = plant use factor.

and,

$$C_s = \frac{FCR \sum_{i=1}^{6} C_i' + I_r \sum_{i=7}^{8} C_i' \sum_{i=9}^{14} C_i'}{C_b \times C_{bo} \times U_f \times 3.65 \times 10^{-4}} \qquad (2)$$

in which C_s = cost of salt removal, \$/metric ton;
C_b = brine flow volume, m^3/day; and
C_{bo} = TDS concentration of brine, mg/ℓ.

The results from the desalting model indicate that costs for either water or salt production are highly affected by plant capacity (scale effects). A plot of these data for a reverse osmosis system having a feedwater salinity of 4000 mg/ℓ is shown in Fig. 1. Analysis of data over a wide possible range of input conditions indicated that functions for the other inputs and processes have the same shape and can be represented by an equation of the following form:

$$C_s = \frac{A}{C_p{}^b} + C \qquad (3)$$

where A, B, and C are emperical regression coefficients.

AGRICULTURAL SALINITY CONTROL COST MODEL

Improved water management and structural rehabilitation are often regarded as the most feasible treatments of the irrigation system for improving the quality of return flows. Indirect approaches such as limiting irrigation diversions, effluent standards, land use regulations, and economic incentives are also being considered although they appear more difficult to implement. Whenever salt pickup is the objective of salinity control,

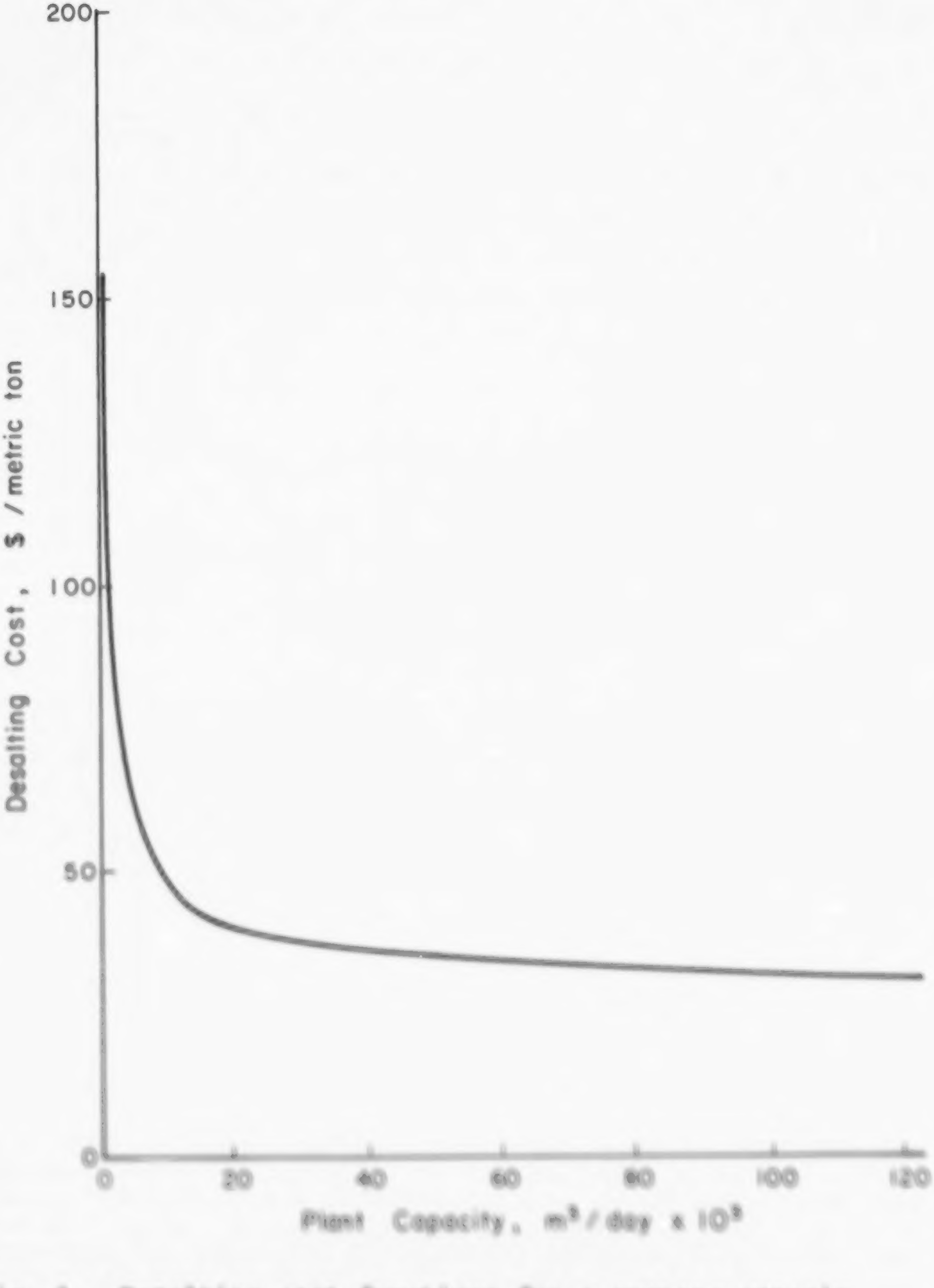

Fig. 1. Desalting cost functions for a reverse osmosis system treating water at 6000 mg/l.

however, the specific control measures should affect sources of groundwater inflow. This may be accomplished by reducing seepage from various elements of the conveyance system and minimizing deep percolation from over-irrigation. Return flow quality may also be improved by relief and interceptor drainage to collect subsurface flows before a chemical equilibrium is reached with the ambient soil or aquifer salinities.

The agricultural salinity control cost model is comprised of cost-effectiveness functions for each alternative. These functions are derived by estimating the cost associated with various levels of control on groundwater inputs and then predicting the reduction in salt loading. For example, the alternative of lining conveyance channels with concrete or gunite is a commonly considered remedy for salinity control and provides both a demonstrative and convenient topic for illustrating the concepts implicit in an agricultural salinity control cost model.

Seepage from canal, lateral, and ditch conveyance networks may be reduced or eliminated by either lining the wetted perimeter with an impervious material or converting to piped systems. Concrete is probably the most commonly employed lining material because of the combined advantages of cost, ease of construction, availability, reduced maintenance, and low permeability. The costs of concrete linings (either slip form or gunite) vary with local economic and topographic conditions, channel geometry and size, and requirements for miscellaneous water management, safety, and environmental structures. For specific locations it is important to prepare cost estimates on a case by case basis, but for planning purposes it is helpful to have generalized expressions. A review of concrete lining costs in the western United States reported by the Bureau of Reclamation (U. S. Department of the Interior, 1963) encompassing a wide range of sizes indicated that these costs could be reasonably well estimated as a function of wetted perimeter and updated to present or future conditions with either USBR or ENR cost indexes. In terms of annual costs,

$$C_c = \frac{FCR \times CI \times WP \times U_c}{2.02} + FCR \times a \qquad (4)$$

in which C_c = amortized construction cost, \$/m of lined length;

FCR = fixed charge rate as defined earlier;

CI = USBR Canal Construction Cost Index;

WP = Wetted perimeter, m; and

a = additional costs per meter of lined length to provide for diversion, control, and safety structures;

U_c = unit cost of lining construction, \$/m^2, where

$$U_c = 5.26 \times WP^{0.283} \qquad (5)$$

Combining equations 4 and 5 gives:

$$C_c = 2.60 \times FCR \times CI \times WP^{1.283} + FCR \times a \qquad (6)$$

Because water is continually being withdrawn from a conveyance channel, the wetted perimeter declines along the length of the channel. The distribution of wetted perimeter may be estimated in a number of ways if measurements are not available. For instance, a linear decline can be assumed or the decrease can be formulated in terms of acreage distributions. Assuming a linear decrease for illustrative purposes, the wetted perimeter at a specific location can be determined by:

$$WP = WP_m(1-bL/L_t) \qquad (7)$$

in which WP_m = the wetted perimeter at the channel inlet, m;

L = length from inlet to specified point, m;

L_t = total length of channel, m; and

b = empirical constant representing the fraction of maximum wetter perimeter remaining at end of the channel.

in this situation, Equation 6 becomes,

$$C_c = 2.60 \times FCR \times CI \times WP_m^{1.283}(1-bL/L_t)^{1.283} + a \times FCR \qquad (8)$$

To express concrete lining costs in terms of salinity control cost-effectiveness relationships, it is necessary to express the cost functions in terms of the corresponding salt loading reduction. The salts removed by seepage control may be written as:

$$\Delta S_1 = \Delta S_c \times V_s \times \left[\frac{Q_g - Q_p}{Q_g}\right] \times 10^{-6} \qquad (9)$$

Where ΔS_1 = reduction in salt loadings due to the linings, metric tons/m annually;

ΔS_c = difference between the equilibrium salinity concentration in the return flows and the salt concentrations in the seepage waters, mg/ℓ;

Q_g = total groundwater additions, m^3/year;

Q_p = phreatophyte use of groundwater, m^3/year; and

V_s = total volume of seepage, m^3/m^2/year, as determined by,

$$V_s = N_d \times \Delta SR \times WP \qquad (10)$$

in which N_d = number of days per year seepage occurs; and

ΔSR = change in seepage rate affected by lining, m^3/m^2/day.

One of the decisions regarding conveyance channel linings is at which end of the system the lining should be initiated. Approximation of the marginal costs as determined by dividing Equation 6 by Equation 9 can be made to answer this question. Let K_1, K_2, and K_3 be defined respectively as,

$$K_1 = 2.60 \times FCR \times CI \times WP_m^{1.283} \tag{11}$$

$$K_2 = \Delta S_c \times N_d \times \Delta SR \times \left(\frac{Q_g - Q_p}{Q_g}\right) \times WP_m \times 10^{-6} \tag{12}$$

$$K_3 = FCR \cdot a \tag{13}$$

Then the marginal costs can be written as:

$$MC = \frac{K_1 \, (1-bL/L_t)^{1.283} + K_3}{K_2 \, (1-bL/L_t)} \tag{14}$$

where MC = marginal costs in \$/ton/m of lined channel. A comparison of MC at the channel inlet and outlet suggests downstream lining direction when MC values are lowest at the upper end, and vise versa.

By knowing the optimal direction of the lining alternative, it is possible to formulate the cost effectiveness function integrating the numerator and denominator of Eqs. 6 and 9 separately. For the downstream lining case, the costs of a specified level of lining are determined by

$$C_{t1} = \int_0^L K_1 \, (1-bl/L_t)^{1.283} dl + \int_0^L K_3 dl \tag{15}$$

or,

$$C_{t1} = \frac{K_1 L_t}{b \times 2.283} \left[1 - (1-bL/L_t)^{2.283}\right] + K_3 L \tag{16}$$

in which C_{t1} = total annual costs of concrete lining for a lined length of L meters in \$ million.

In a similar manner,

$$S_L = \int_0^L K_2 dl - \int_0^L \frac{K_2 bl}{L_t} dl \tag{17}$$

or,

$$S_L = K_2 L - \frac{K_2 L^2 b}{2 . L_t} \tag{18}$$

where S_L = annual salt loading reduction in tons.

If the optimal lining direction is upstream, the costs of and salt loading reductions are determined by evaluating Eq. 5 between the limit of L_t and L, so that:

$$C_{t1} = \frac{K_1 L_t}{2.283b} \left[(1-b)^{2.283} - (1-bL/L_t)^{2.283}\right] + K_3(L_t-L) \qquad (19)$$

Likewise for the salt loading function, Eq. 17 is evaluated between the limit L_t and L to give:

$$S_L = K_2(L_t-L) - \frac{K_2 b}{2L_t}(L_t{}^2 - L^2) \qquad (20)$$

INTEGRATION OF AGRICULTURAL AND DESALINATION TECHNOLOGIES

Conceptual Model

Before concluding this paper with an analysis of optimal salinity control strategies in the Grand Valley of Western Colorado, it is probably relevant to develop the conceptual model in which this analysis would be applied. The concept of "optimal" implicitly assumes a systematic comparison of alternatives based on a common objective criterion, The procedures for such comparisons are generally referred to as "systems analyses" or "operations research."

On a basin-wide scale, a salinity problem is the combined effect of many irrigated areas, saline springs, diffuse natural inflows, and other miscellaneous sources. These salinity sources not only occur sequentially due to the geographic structure of an hydrologic area, but are also often governed by differing administrative formulas. Consequently, the problem of determining an "optimal" strategy for a large area like the river basin rapidly becomes too large and too complex for direct analysis. One of the various mathematical techniques for optimizing complicated systems is to decompose the problem into a series of subproblems whose solutions are coordinated in a manner that produces the solution to the larger problem. Most readers are undoubtedly familiar with many of these techniques; dynamic programming being one of the most effective. One method applied to analysis of water quality improvements in the Utah Lake Drainage basin of central Utah provides both a simple and effective decomposition (Walker et al. 1973). The structure of the decomposition methodology referred to above is shown schematically in Fig. 2. Individual levels of modeling are delineated to define water quality cost-effectiveness analyses at different stages of development in route to a single representation at the ultimate basin-wide scale. Analysis begins at the lowest level of administration such as an individual irrigation district. Within this area, the cost-effectiveness function describing the alternative measures for controlling water quality are combined in an optimization analysis to determine the best policy for management in the district. This is accomplished by determining optimal strategies over the entire range of possible degrees of control. The optimal costs versus quality control effectiveness relationship expresses the level 1 cost-effectiveness function for the area or firm under consideration. This analysis is repeated to integrate the level 1 functions in formulating the level 2 cost-effectiveness relationships.

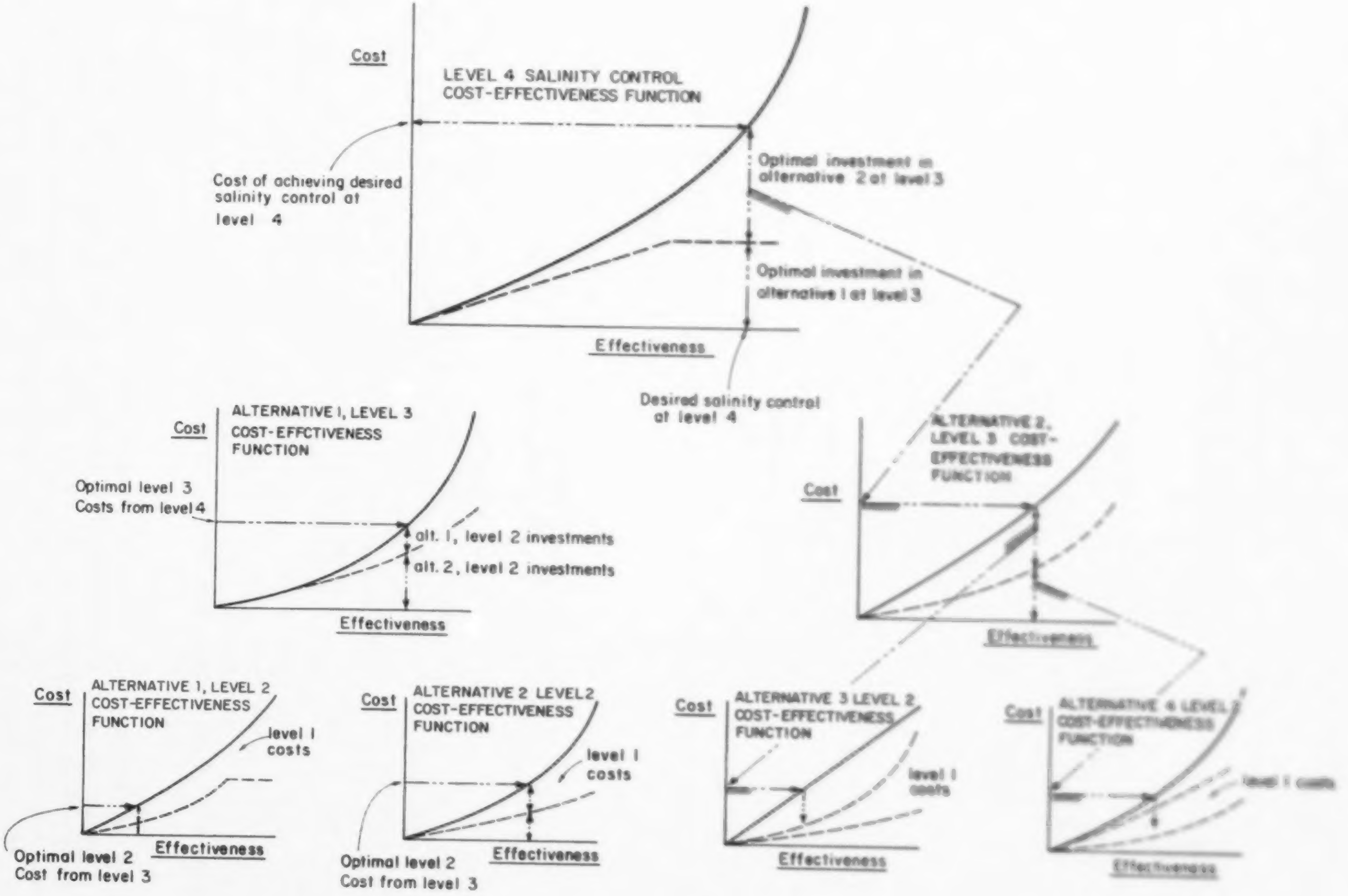
Cost
LEVEL 4 SALINITY CONTROL
COST-EFFECTIVENESS FUNCTION
Cost of achieving desired salinity control at level 4
Optimal investment in alternative 2 at level 3
Optimal investment in alternative 1 at level 3
Effectiveness
Desired salinity control at level 4
Cost
ALTERNATIVE 1, LEVEL 3
COST-EFFCTIVENESS FUNCTION
Optimal level 3 Costs from level 4
alt. 1, level 2 investments
alt. 2, level 2 investments
Effectiveness
ALTERNATIVE 2, LEVEL 3 COST-EFFECTIVENESS FUNCTION
Cost
Effectiveness
Cost
ALTERNATIVE 1, LEVEL 2
COST-EFFECTIVENESS FUNCTION
level 1 costs
Optimal level 2 Cost from level 3
Effectiveness
Cost
ALTERNATIVE 2 LEVEL 2
COST-EFFECTIVENESS FUNCTION
level 1 costs
Optimal level 2 Cost from level 3
Effectiveness
Cost
ALTERNATIVE 3 LEVEL 2
COST-EFFECTIVENESS FUNCTION
level 1 costs
Effectiveness
Cost
ALTERNATIVE 4 LEVEL 2
COST-EFFECTIVENESS FUNCTION
level 1 costs
Effectiveness

Fig. 2. Schematic illustration of a decomposition principle applied to the development of salinity control strategies.

For instance, in an irrigated area, the optimized level 1 strategies for controlling salinity from each of its districts along with other alternatives at the irrigated area scale, such as desalination, are integrated to determine the best area-wide policy for salinity control. Again, the analysis is made over the possible range of salinity reductions to establish the relationship. The results of level 2 analyses can then be integrated to develop level 3 functions and so on until the desired level is reached.

The cost-effectiveness functions at each level are composed of two parts. The first is the relationship between the costs and resulting salinity reductions, while the second is the "policy space" plotted under this curve. For example, at level 4 in Fig. 2, the curve represents the minimal costs necessary to reduce salinity to the desired level. At that point, a vertical line delineates the respective investments to be made in the various level 3 alternatives. If both level 3 alternatives are irrigated valleys, the policy space indicates how much should be spent in each valley. Then going to level 3 results as determined from the level 4 relationship, it is possible to delineate the breakdown of these expenditures into treatments of the alternatives at the 2nd level, etc.

For the case study example in the Grand Valley, this procedure will be demonstrated for a partial analysis of level 1 and 2 alternatives involving conveyance lining and desalination.

Description of Case Study Area

The Grand Valley is one of the most significant contributors to the problem of salinity in the Colorado River Basin (Fig.3). The region's low annual precipitation (250mm) and high rates of evapotranspiration during the growing season (often up to 13mm/day) demonstrate the importance of irrigation for the 25,000 ha of alfalfa, corn, sugar beets, small grains, and deciduous orchards (Walker and Skogerboe, 1971). Most of the cropland is furrow irrigated although border, sprinkler, and trickle irrigation methods are being evaluated. The soils are generally of a silty-clay variety characterized by high salinities and low infiltration rates (Skogerboe and Walker, 1972). Irrigation water is delivered to the croplands through a system of unlined canals, laterals, and ditches. For example, most of the irrigated area is served by diversions from the Colorado River into the Grand Valley or Government Highline Canals, from which many irrigators withdraw water directly into the lateral system leading to the individual farms. Occasionally, the large canals divert water into smaller ditches or canals to improve distribution of water to the laterals. A summary of the conveyance characteristic in the Grand Valley is given in Table 2.

The high salt content of soil and aquifer materials combine with poor irrigation efficiencies to also cause severe salinity damages locally. Local as well as downstream salinity impacts can be attributed to two conditions. First, soil and aquifer materials are primarily derived from the underlying Mancos Shale formation. The shale is of marine origin and contains large volumes of crystalline salt in its layered structure.

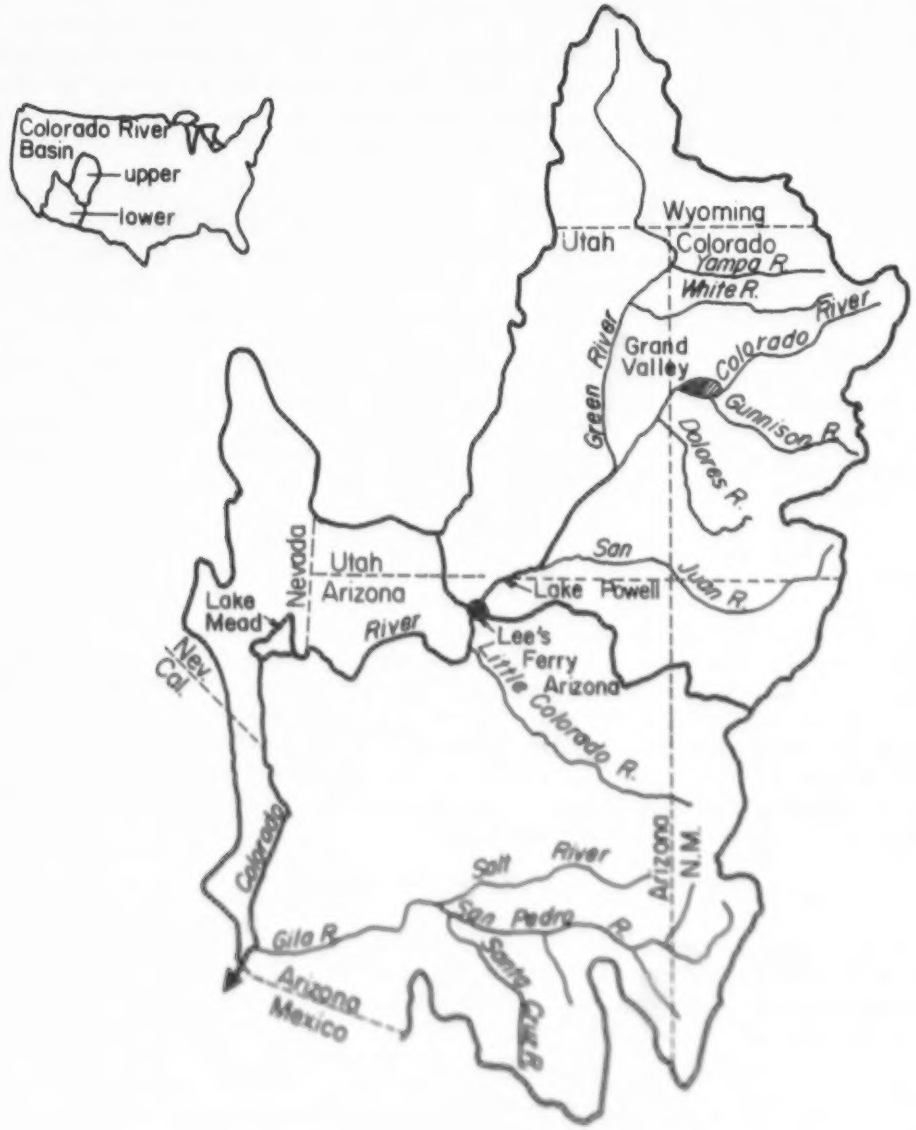
Colorado River Basin
upper
lower
Wyoming
Utah
Colorado
Yampa R.
White R.
River
Grand Valley
Colorado
Green River
Gunnison R.
Dolores R.
San
Juan R.
Nevada
Utah
Arizona
Lake Powell
Lake Mead
River
Lee's Ferry
Arizona
Little Colorado R.
New.
Cal.
Colorado
Salt
River
Arizona
N.M.
San Pedro
R.
Gila R.
Santa Cruz R.
Arizona
Mexico

Fig. 3. Location and setting of Colorado's Grand Valley.

Any irrigation return flows passing through the subsurface areas, therefore, dissolve and convey large quantities of salts to the river. The second local condition is that the volume of return flow is high because of poor irrigation practices. While suburban growth and industrial development along with ineffective drainage have reduced irrigated acreage by approximately 50% since 1882, diversions have remained about the same. The obvious excesses have promoted the poor irrigation practices.

The agricultural hydrology of the valley is difficult to define from inflow-outflow budgeting because the river inflows are so large in comparison to irrigation requirements. Consequently, much of the existing information concerning the water and salt systems has been derived from intensive investigations on the irrigated lands themselves. Several of the most recent studies include the application of a hydro-salinity model by Walker (1970), and an evaluation of conveyance and on-farm water management by Skogerboe et al. (1972; 1974a; and 1974b). Based largely upon these analyses, Westeson (1975) developed water and salt budgets representative of the valley under normal conditions. The water phase of this budget is illustrated in Fig. 4.

Flows entering the valley in the Colorado and Gunnison Rivers contain a weighted average salinity concentration of 57[illegible] mg/ℓ and leave with a concentration of 750 mg/ℓ . A mass balance comparison of inflows and outflows indicate a salt pickup of more than 630,000 metric tons. It is generally assumed that the salt pickup can be attributed to the subsurface irrigation return flow caused by seepage and deep percolation. A check on this assumption and the reliability of the budgeting leading to Fig. 4 can be made by comparing calculated values of groundwater salinity with measured values over a six year period. The results of the calculations predict a salinity concentration of approximately 7,500 mg/ℓ which agrees reasonably well with the groundwater data.

GRAND VALLEY RESULTS

Conveyance lining. Based upon data thought to be representative of the general Grand Valley conditions, values of K_1, K_2, and K_3 were evaluated by Equations 11-13. Then Equations 15, 18, 19, and 20 were solved for the upstream and downstream linings in each of the conveyance networks. The choice of direction was determined by Equation 14. And finally, a range of L values in these equations was evaluated to provide data which could be evaluated to determine the relationship between annual costs and expected salt loading for each canal, lateral, or ditch. In evaluating these data, it was found that the following function accurately predicted the conveyance lining cost-effectiveness:

$$C_{tl} = aS_L^c \qquad (21)$$

and the regression coefficients along with a summary of other model inputs are shown in Table 3.

The individual cost-effectiveness functions of the conveyance network were formulated into an optimizational analysis where the minimal costs

Table 2. Characteristics of Grand Valley canals, laterals and ditches.

Canal, Lateral or Ditch	Length (K_m)	Inlet discharge (m^3/sec)	Terminal discharge (m^3/sec)	Average wetted perimeter (m)	Average seepage rate (m^3/m^2/day)	Total seepage[2/] (m^3/day)	Total salt pickup/yr (metric tons)
Government Highline Canal	73.7	19.8	.7	13.8	.076	77,300	53,920
Price Ditch	14.5	1.7	.3	5.1	.046	3,400	2,370
Stub Ditch	16.4	0.6	.1	2.7	.046	2,040	1,420
Orchard Mesa #1 Canal	26.2	2.3	.2	4.6	.061	7,350	5,130
Orchard Mesa #2 Canal	27.8	1.7	.2	2.8	.061	4,750	3,310
Grand Valley Canal	19.8	18.4	14.1	18.3	.030	10,870	7,580
Independent Ranchmen's Ditch	18.8	2.0	.8	3.0	.046	2,590	1,810
Kiefer Extension of G.V. Canal	24.8	4.0	.7	6.0	.046	6,840	4,770
Highline of G. V. Canal	37.5	8.5	4.0	12.8	.046	22,080	15,400
Mainline of G. V. Canal	22.2	7.1	.7	10.6	.046	10,830	7,550
Mesa County Ditch	6.8	0.8	.06	3.0	.046	440	660
Redlands 1st & 2nd Lift Canals	31.4	1.7	.06	5.1	.122	19,540	13,630
Total	319.9					168,530	117,550
Unlined conveyance laterals	640	0.17	0	1.8	.152	175,100	122,130
Unlined Farm Head Ditches	925	0.03	0	1.2	.304	168,720	117,670
Total	1565					343,820	239,800
					Total	512,350	357,350

2/ Rates based on 183 day season for canals, laterals, and ditches, and
91 day season for farm head ditches

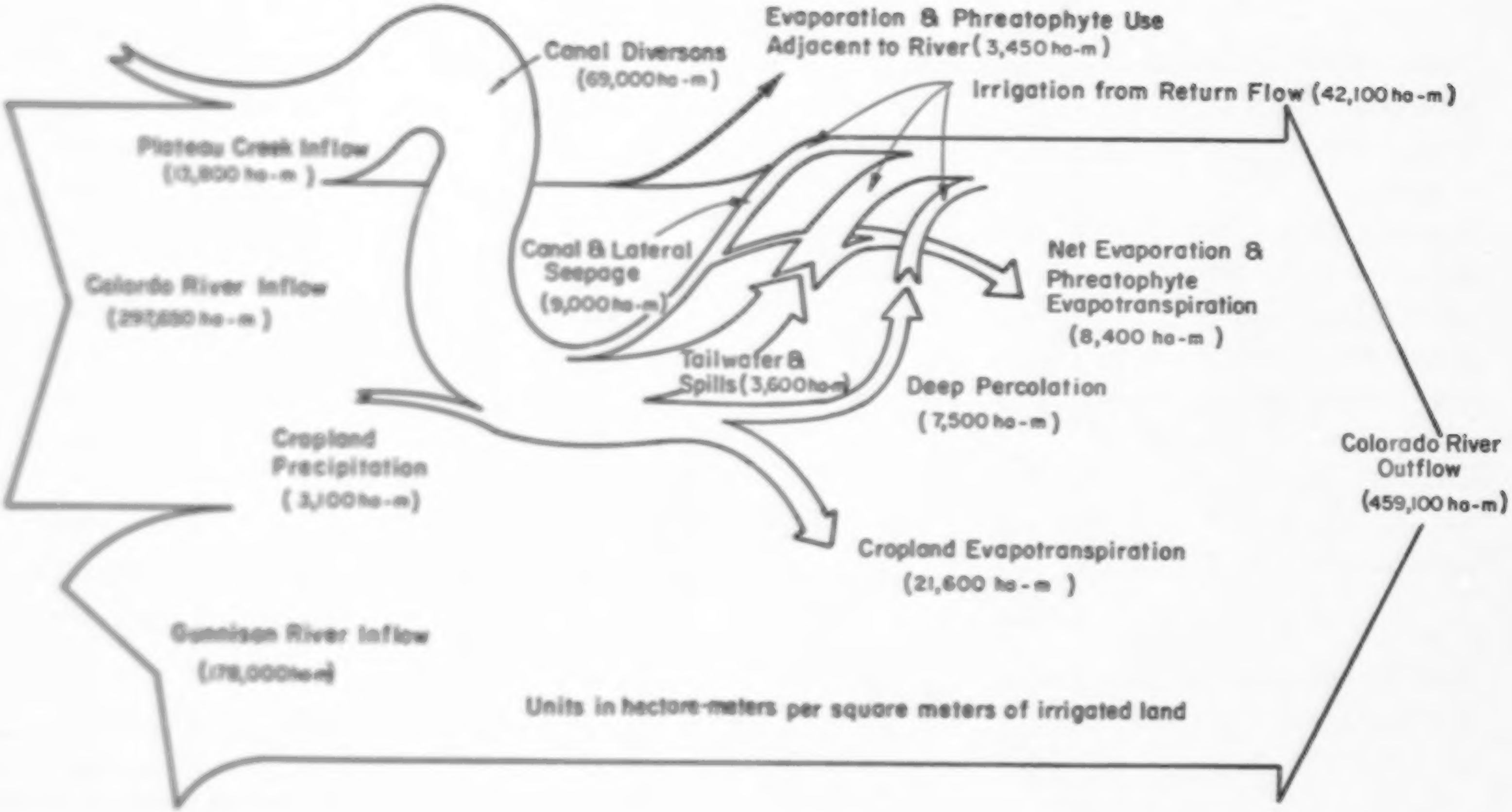
Canal Diversons
(69,000 ha-m)
Evaporation & Phreatophyte Use
Adjacent to River (3,450 ha-m)
Irrigation from Return Flow (42,100 ha-m)
Plateau Creek Inflow
(13,800 ha-m)
Canal & Lateral
Seepage
(9,000 ha-m)
Net Evaporation &
Phreatophyte
Evapotranspiration
(8,400 ha-m)
Colorado River Inflow
(297,650 ha-m)
Tailwater &
Spills (3,600 ha-m)
Deep Percolation
(7,500 ha-m)
Cropland
Precipitation
(3,100 ha-m)
Colorado River
Outflow
(459,100 ha-m)
Cropland Evapotranspiration
(21,600 ha-m)
Gunnison River Inflow
(178,000 ha-m)
Units in hectare-meters per square meters of irrigated land

Fig. 4

Table 3. Summary of conveyance lining cost-effectiveness data for Grand Valley case study.

Name of Canal, Ditch or Lateral	Length (Km)	Maximum Wetted Perimeter (m)	Total Salt Loading (tons)	K_1	K_2	K_3	b	$a^{3/}$	$c^{3/}$
Government Highline Canal	73.7	20.0	53,920	24.520	1.2175	5.0	0.798	21.42	1.012
Price Ditch	14.5	7.0	2,370	6.377	0.24177	0	0.6479	12.73	1.067
Stub Ditch	16.4	3.7	1,420	2.814	0.1278	0	0.645	11.69	1.073
Orchard Mesa Canal #1	26.2	9.5	5,130	9.435	0.3560	3.0	0.90	25.02	1.045
Orchard Mesa Canal #2	27.8	7.0	3,310	6.377	0.2165	3.0	0.90	16.88	1.130
Grand Valley Canal	19.8	20.0	7,580	24.520	0.4505	5.0	0.30	45.59	1.005
Independent Ranchmen's Ditch	18.8	8.2	1,810	7.811	0.1750	2.0	0.90	31.27	1.084
Kiefer Extension of Grand Valley Canal	24.8	10.0	4,770	10.077	0.3454	3.0	0.8863	16.61	1.105
Grand Valley Highline Canal	37.5	14.0	15,400	15.517	0.4835	3.0	0.3013	37.46	1.001
Grand Valley Mainline Canal	22.2	12.0	7,550	12.733	0.4145	3.0	0.3590	37.45	1.002
Mesa County Ditch	6.8	3.7	660	2.814	0.1278	0	0.4811	16.03	1.035
Redlands 1st & 2nd Lift Canals	31.4	7.0	13,630	6.377	0.6412	3.0	0.646	7.32	1.081
Conveyance Lateral System	640.0	1.8	122,130	1.116	0.2054	0	0.1419	4.94	1.006
Farm Head Ditch Lateral System	925.0	1.2	117,670	0.664	0.1370	0	0.1629	4.47	1.005

3/ Conveyance channel cost-effectiveness function, cost ($/year) = a(Salt Loading Reduction, metric tons/year)^c.

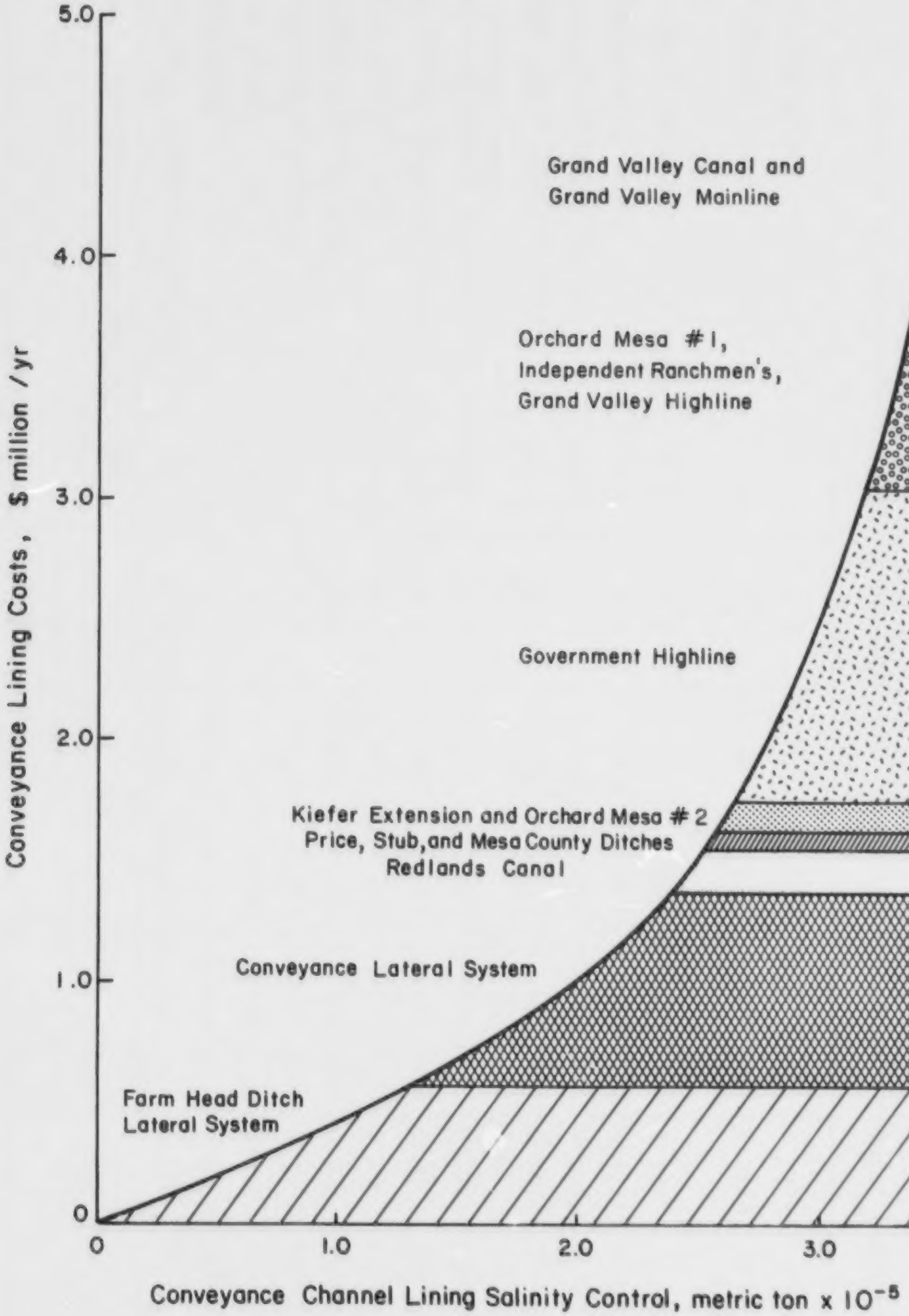

Fig. 5. Optimal conveyance channel lining policy for system in the Grand Valley, Colorado.

and optimal lining strategies were determined. The objective function was written:

$$Y = \min \sum_{i=1}^{14} a_i S_{L_i}^{c_i} \qquad (22)$$

where a_i = coefficient for the ith conveyance segment in Table 3;

S_{Li} = salt loading to be reduced as a result of lining the ith channel (decision variable);

c_i = exponent for the ith canal, lateral, or ditch; and

Y = minimum lining cost, \$/million annually.

The optimization equation was also subject to the following constraints:

$$\sum_{i=1}^{14} S_{Li} = \bar{S}_L \qquad (23)$$

$$S_{Li} \leq S_{Lt} \quad , i = 1, 2, \ldots, 14 \qquad (24)$$

in which $\bar{S}_L$ in the total desired salinity reduction anticipated from conveyance linings, and S_{Lt} is the maximum salt loading from the individual lined channels (see Table 3, Column 4). Because the objective function is non-linear and the constraints are mixed equalities and inequalities, the optimization technique utilized to determine Y was the Jacobian Differential Algorithm developed by Walker (1973).

When the value of $\bar{S}_L$ was ranged from 0-357,000 tons, data for a function of Y versus $\bar{S}_L$ were generated. A plot of these data is shown in Fig. 5. The policy space is plotted under the minimum cost curve to indicate at what level of desired salt loading for the conveyance alternative each segment should be lined. For example, if the desired salt loading reduction was 325,000 tons, the total expenditures would be \$3.25 million annually. This cost should optimally be distributed according to the vertical distribution of costs for each of the conveyance systems. Thus, at a $\bar{S}_L$ of 325,000 tons, the farm head ditch lateral system (\$.57 million, 117,670 tons), conveyance lateral system (\$.805 million, 122,130 tons), Redlands Canals (\$.175 million, 13,630 tons), Price, Stub, and Mesa County ditches (\$.075 million, 4.450 tons) Kiefer extension and Orchard Mesa #2 canals (\$.125 million, 8,080 tons) Government Highline Canal (\$1.28 million, 53,920 tons), and the Orchard Mesa #1 Canal (\$.22 million, 5.120 tons) should be lined. If the remaining 32,000 tons of salt contributable to the conveyance system are to be removed, the other canals would require lining.

Desalination. An evaluation of alternative desalting methods in the Grand Valley case indicated that reverse osmosis would exhibit the lowest costs over the range of potential applications. Furthermore, the use of a single plant rather than multiple plants located throughout the valley was determined to be the best use of the technology even though the cost of feedwater facilities would be greater. A desalting cost-effectiveness function similar to Fig. 5 was developed from the model presented earlier in Table 1 and a similar model for feedwater and brine disposal facilities using well systems. This curve is shown in Fig. 6.

It is important to compare the respective shapes of Figs. 5 and 6 prior to the final phase of this analysis. In Fig. 5, the lining costs exhibit increasing marginal costs with scale while the curve in Fig. 6 representing desalination indicates decreasing marginal costs with scale. In optimizing the use of each technology, it is therefore important to note that low levels of salinity control will favor the use of agricultural improvements whereas high levels will require desalination.

Optimization of agricultural and desalination cost-effectiveness functions. If on a valley wide basis the two salinity control alternatives were conveyance lining and desalting, then the optimal policy for incorporating each into the program for salinity control would be determined by an analysis similar to that shown previously in Eqs. 22-24. This was accomplished for salt loading reduction up to approximately 630,000 tons and the integrated results are shown in Fig. 7.

These results are interesting in demonstrating the multi-level optimizational concepts described in an earlier section. The importance of planning for salinity control on a basin-wide scale as a prerequesite to deciding upon a local program is clearly illustrated in the Grand Valley case study. For example, the optimal strategy locally depends on the comparative feasibility of salinity control in the valley with other areas and salinity sources. Thus, the results of integrating the local feasibilities into an optimal strategy for a basin determines the salt loading reduction needing to be achieved locally and the investments in the respective technology necessary to meet this objective. The importance of complete analysis in this respect can be demonstrated by re-examining Figs. 6 and 7. Suppose a planner without the benefits of an analysis such as proposed here decided that a 350,000 ton reduction should be accomplished by conveyance lining alone. The costs would be about $4.3 million on an annual basis or about 30% higher than a combined agricultural-desalination program.

SUMMARY

The use of multi-level optimizational modeling is demonstrated for a case study involving the alternatives of agricultural and desalination technologies for controlling salinity in the Grand Valley of western Colorado. The results illustrate the non-linear, and thus, non-intuitive nature of the decision making process of salinity management. These results also suggest that broader perspective modeling analyses are needed prior to deciding upon local and regional water quality management decisions. Analysis at this level of investigation implies that sufficient modeling of complex hydro-chemical systems has been successively undertaken to

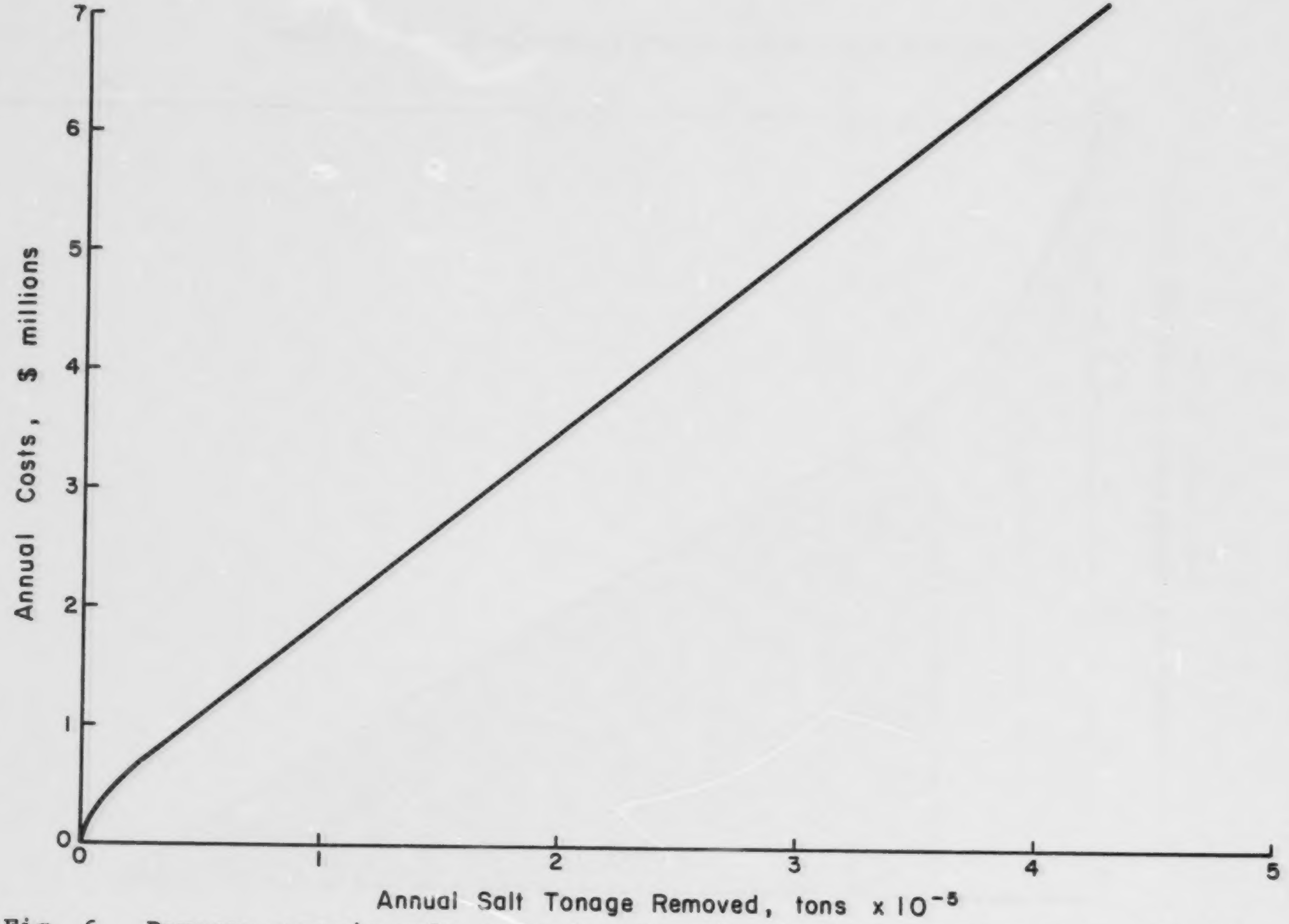

Fig. 6. Reverse osmosis salt removal cost effectiveness function for application in the Grand Valley.

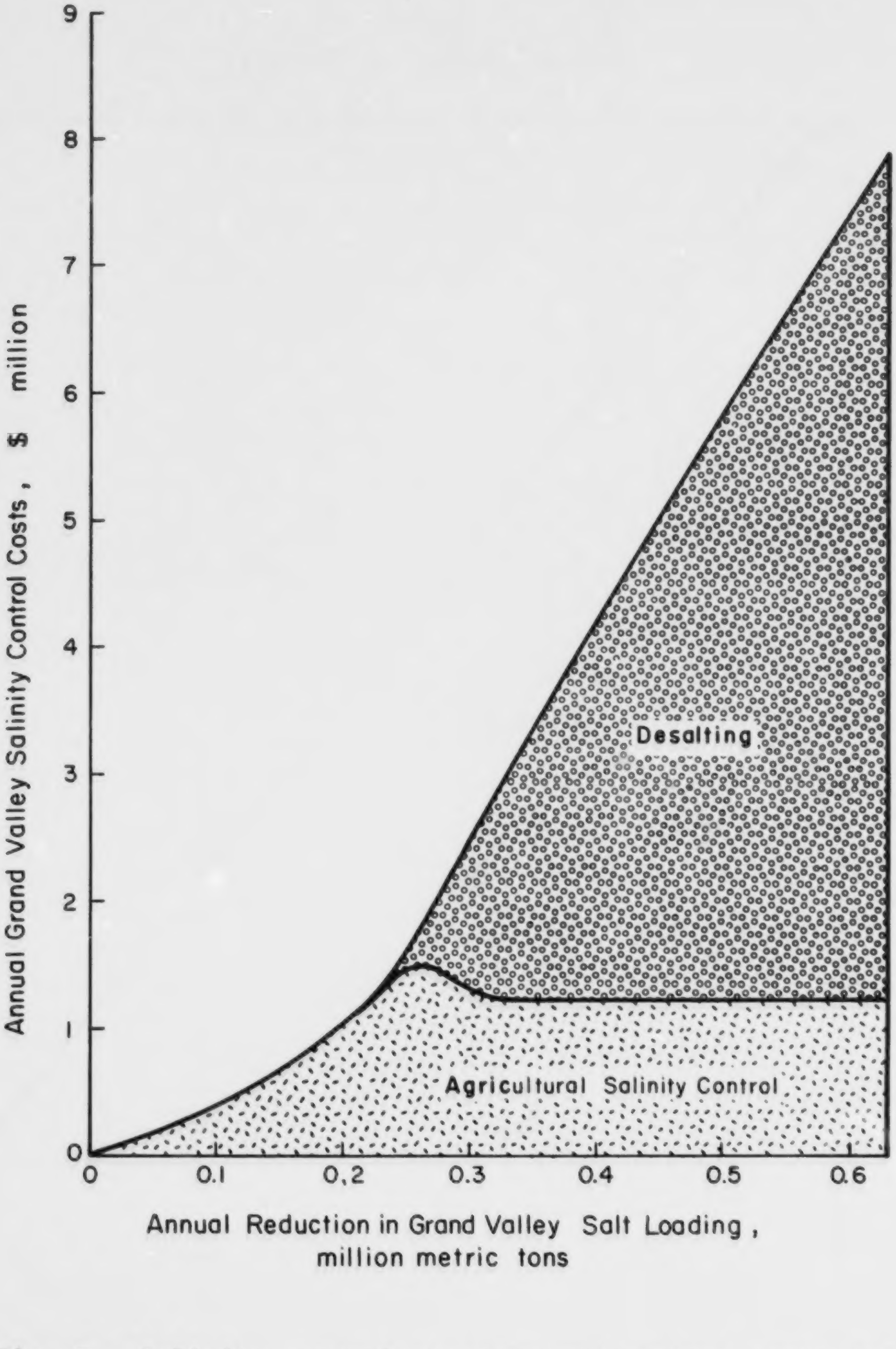

Fig. 7. Salinity control strategy and optimal costs for the Grand Valley.

generate appropriate inputs. However, decisions are often required before total verification of these detailed models can be achieved. It, therefore, appears that better efforts should be made to not only coordinate research between disciplines, but also in terms of eventual use of research data utilization.

ACKNOWLEDGEMENTS

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LITERATURE CITED

Prehn, W. L., J. L. McGaugh, C. Wong, J. J. Strobel, and E. F. Miller. 1970. Desalting Cost Calculating Procedures. Research and Development Progress Report No. 555. Office of Saline Water, U. S. Department of the Interior, Washington, D. C. May.

Skogerboe, G. V. and W. R. Walker. 1972. Evaluation of Canal Lining for Salinity Control in Grand Valley. Environmental Protection Technology Series Report 13030 DOA01-72. Environmental Protection Agency, Washington, D. C. October.

Skogerboe, G. V., W. R. Walker, J. H. Taylor, and R. S. Bennett. 1974a. Evaluation of Irrigated Scheduling for Salinity Control in Grand Valley. Environmental Protection Technology Series Report EPA-660/2-74-052. Environmental Protection Agency, Washington, D. C. June.

Skogerboe, G. V., W. R. Walker, R. S. Bennett, J. E. Ayars, and J. H. Taylor. 1974b. Evaluation of Drainage for Salinity Control in Grand Valley, Environmental Protection Technology Series Report EPA-660/2-74-084. Environmental Protection Agency, Washington, D. C. August.

Walker, W. R. 1970. Hydro-Salinity Model of the Grand Valley. Unpublished M. S. Thesis, Civil Engineering Department, Colorado State University, Fort Collins, Colorado. August.

Walker, W. R. and G. V. Skogerboe. 1971. Agricultural Land Use in the Grand Valley. Report No. AER71-72WRW-GVS1, Agricultural Engineering Department, Colorado State University, Fort Collins, Colorado. July.

Walker, W. R. 1973. Mathematical Modeling of Urban Water Management Strategies. Unpublished Ph.D. Dissertation. Agricultural Engineering

Department, Colorado State University, Fort Collins, Colorado. August.

Walker, W. R., T. L. Huntzinger, and G. V. Skogerboe. 1973. Coordination of Agricultural and Urban Water Quality Management in the Utah Lake Drainage Area. Technical Completion Report Series 46. Environmental Resources Center, Colorado State University, Fort Collins, Colorado. June.

Westeson, G. L. 1975. Salinity Control for Western Colorado. Unpublished Ph.D. Dissertation, Agricultural Engineering Department, Colorado State University, Fort Collins, Colorado. June.

U. S. Department of the Interior, Bureau of Reclamation. 1963. Linings for Irrigation Canals. U. S. Government Printing Office, Washington, D. C.

U. S. Department of the Interior, Bureau of Reclamation and Office of Saline Water. 1972. Desalting Handbook for Planners. Denver, Colorado. May.

EFFECTS OF IRRIGATION LEACHING MANAGEMENT ON RIVER AND SOIL WATER SALINITY

D. L. Suarez and J. D. Rhoades [1]

INTRODUCTION

Rhoades et al., (1973, 1974) demonstrated that the salt burdens of percolated irrigation drainage waters could be appreciably reduced by reducing the leaching fraction (LF) - the fraction of infiltrated water that passes the root zone. Computer models predict the same effects (Oster and Rhoades, 1975). Minimizing the quantity of drainage water reduces the quantity of applied salts contained in it.

Improved irrigation efficiency has been advocated as a way to reduce demands for water diversion from rivers, reduce volume of drainage return flow to be disposed of, and reduce loss of soluble nutrients, especially nitrate (van Schilfgaarde et al., 1974).

These findings pertain to the salt loadings of percolated drainage waters. This paper provides information about the effects of irrigation management on the changes in river water, soil water, and groundwater quality associated with successive downstream water diversion for representative types of river waters. The deposition of $CaCO_3$ and gypsum in entire river basins as a function of leaching fraction is also considered.

METHOD OF CALCULATIONS AND ASSUMPTIONS

Soil and drainage water compositions and the extent of $CaCO_3$ and gypsum precipitation and dissolution were calculated using the model described by Oster and Rhoades (1975). Gypsum was assumed to be initially absent in calcareous soils. Rivers were classified into three groups: Type 1 - rivers initially undersaturated with $CaCO_3$, Type 2 - rivers initially saturated with $CaCO_3$, and Type 3 - rivers initially saturated with $CaCO_3$ and nearing saturation with gypsum. The three such hypothetical rivers considered resembled the Feather, Rio Grande and Pecos rivers, respectively. The initial chemical compositions of the three river types are given in Table 1. Initial annual river volumes entering the upstream river systems were assumed to be 1.23×10^9 m^3 (1,000,000 acre-feet). Each of nine consecutive downstream irrigation projects of 10,100 hectares (25,000 acres) were assumed to consume 1.23×10^8 m^3 (100,000 acre-feet) annually. It was further assumed that long term use of these waters had resulted in steady-state conditions, so that the drainage flow from each project was completely returned to the river below each project; that the resulting river water re-equilibrated and had a CO_2

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level of 0.1 percent before it arrived at the next downstream project; and that the compositions of drainage waters were due solely to concentration of the irrigation water by evapotranspiration, precipitation of calcium carbonate and gypsum, or dissolution of calcium carbonate (Undoubtedly actual rivers receive downstream inputs of salt and water from other sources such as dissolution of soluble minerals present in subsurface strata, saline springs, etc.) The leaching fractions were taken as 0.1 and 0.4 for low and high leaching management, respectively.

Compositions of soil waters were calculated for the bottom of each of four 30 cm (1-foot) intervals through the assumed 120 cm root zone. The water uptake distribution within the root zone was assumed to be the same for low and high leaching (Rhoades and Merrill, 1975). This resulted in LF's at the lower boundary of each of the soil intervals of 0.64, 0.37, 0.19, and 0.10 for 10% leaching, and 0.76, 0.58, 0.46, and 0.40 for 40% leaching. The CO_2 distribution was assumed to be 1%, 1.5%, 2.3%, and 3%, respectively, for each successive interval.

The differences in the products of volume and concentration of soil waters at successively deeper soil intervals were used to calculate the absolute amounts of $CaCO_3$ and gypsum precipitation occurring in each soil interval. The differences between the products of volume and concentration of irrigation and drainage water at the lower boundary of the bottom interval were used to calculate the net loss or gain of salt in the soil profile. This distinction is made because leaching dissolves some additional $CaCO_3$ in the upper soil intervals that is subsequently precipitated in lower depths. This salt deposition does not represent salt removed from the irrigation water, but it does contribute to loss of soil porosity. For this reason, it is considered in contrasting the deposition differences between low and high leaching.

Table 1: Chemical Compositions of the Three River Types above the First Diversion Point.

River Type	meq/l					
	Ca	Mg	Na	Cl	Alkalinity	SO_4
1	0.45	0.36	0.25	0.04	0.86	0.16
2	2.18	0.60	1.05	0.21	2.31	1.31
3	8.48	1.56	1.52	1.05	2.08	8.43

RESULTS

Compositions of the river waters at representative downstream locations for low and high leaching management are given in Table 2. As expected, as a consequence of evapotranspiration and removal of $CaCO_3$ and $CaSO_4$ by precipitation, all rivers increased in salinity (see sum of cations)

Table 2. Compositions of River Waters by Downstream Locations. Analyses in meq/l.

Location Below Diversion No.	Ca	Cl	Alkalinity	SO_4	Σcations	SAR[1/]
Type 1 River; LF = 0.1						
2	.56	.04	1.08	.20	1.32	.44
5	.75	.07	1.56	.32	1.95	.57
9	.87	.36	4.91	1.58	6.85	1.63
Type 1 River; LF = 0.4						
2	1.31	.04	1.83	.20	2.07	.33
5	1.78	.07	2.61	.32	2.98	.44
9	.85	.36	5.06	1.58	6.83	1.63
Type 2 River; LF = 0.1 and LF = 0.4						
2	2.27	.26	2.43	1.64	4.34	1.07
5	2.27	.42	2.54	2.62	5.58	1.60
9	2.09	2.06	3.49	13.1	18.6	5.24
Type 3 River; LF = 0.1						
2	8.52	1.32	1.64	9.41	12.4	.83
5	9.45	2.11	1.64	11.9	15.6	1.21
9	12.1	10.6	1.85	30.5	42.9	4.08
Type 3 River; LF = 0.4						
2	9.60	1.32	1.59	10.5	13.5	.79
5	14.3	2.11	1.48	16.9	20.4	1.03
9	24.4	10.6	1.80	43.1	55.2	3.40

[1/] SAR = Na+ / $\sqrt{(Ca^{2+} + Mg^{2+})/2}$, with all concentrations in meq/liter. SAR is an index of the sodicity hazard of a water.

and sodicity downstream (U.S. Salinity Laboratory Staff, 1954; **Rhoades**, 1972). Such trends are typical of most natural river systems (Rhoades and Bernstein, 1971). Whether or not there are differences in salinity and sodicity between low (LF = 0.1) or high (LF = 0.4) leaching management depends on the initial composition of a river. Type 1 rivers are lower in salinity and higher in sodicity with low leaching than with high leaching. The higher levels of salinity (3 to 78%) and higher proportion of calcium and bicarbonate at high leaching results from $CaCO_3$ dissolution. In this case the river is initially undersaturated with $CaCO_3$ and thus could increase its Ca and HCO_3 content, as will be shown later. Thus for rivers of this type, downstream salinity can be reduced (though the magnitude is small) by reducing the leaching fraction.

The composition of the Type 2 rivers, on the other hand, was the same with either high or low leaching management because it was initially saturated with $CaCO_3$. Although more salt was discharged from the soil profile in the drainage water with high leaching, it was subsequently removed from solution in the river as a result of $CaCO_3$ precipitation upon exposure there to a CO_2 concentration lower than existed in the soil system. For Type 2 rivers decreased leaching does not reduce salt load. In the Type 3 rivers, low leaching substantially reduced (4% to 42%) salt load due to increased precipitation of gypsum in the soil. The SAR's of the river increased with reduced leaching, but not to levels that would cause concern.

Compositions of the soil waters and irrigation drainage effluents at four soil depths for low and high leaching management are given in Table 3. Salinity and sodicity of the soil water increases downstream for all river types. In no case however did salinity and sodicity approach levels harmful to either crop yield or soil permeability. The higher SAR's at the lower depths should not cause permeability problems because of the compensating higher salinity level. The concentration of the soil waters at the bottom of the fourth depth (the drainage waters) were lower for all river types with high leaching. The salt load (concentration x volume) however is reduced with low leaching; this phenomenon has been discussed previously (Rhoades et al., 1973, 1974; Oster and Rhoades, 1975). If this water could be intercepted and kept from the river, the salinities of the river systems could be appreciably lowered. It is the successive mixing of these drainage waters with the undiverted rivers and readjustment to near-atmospheric CO_2 levels that result in the downstream trends in the river compositions given in Table 2. Although reduced leaching increases the salt concentration of drainage return, the absolute discharge of salt is less because the concentration increase is less than the proportional volume decrease. This may or may not have a desirable effect on groundwater, but when the drainage is returned to a river it may reduce its salinity in the manner discussed previously.

Gains and losses of salt by soils and rivers within projects at successive downstream locations for low and high leaching management are given

Table 3. Composition of Soil Waters by Quarter Depths in the Rootzone, Analysis in meq/l.

Diversion No.	Depth	Ca	Σcations	Cl	Alkalinity	SO_4	EC[1/]	SAR[2/]
Type 1 River; LF = 0.1								
5	1	4.0	5.6	.1	5.1	.4	.5	.4
	2	4.3	7.0	.2	6.1	.7	.6	.6
	3	4.4	9.6	.3	7.9	1.4	.8	1.1
	4	3.8	13.8	.6	10.5	2.7	1.1	1.9
Type 1 River; LF = 0.4								
5	1	4.1	5.4	.1	5.0	.4	.5	.4
	2	4.6	6.4	.1	5.8	.5	.6	.4
	3	5.3	7.6	.1	6.8	.6	.7	.5
	4	5.8	8.4	.2	7.5	.7	.7	.6
Type 2 River; LF = 0.1								
5	1	4.8	9.1	.5	5.1	3.4	.8	1.5
	2	5.6	13.1	.9	6.2	5.9	1.1	2.2
	3	6.6	21.2	1.8	7.9	11.5	1.7	3.6
	4	7.4	35.0	3.5	9.7	21.8	2.8	5.6
Type 2 River; LF = 0.4								
5	1	4.8	8.4	.5	5.1	2.9	.7	1.3
	2	5.5	10.3	.6	5.9	3.8	.9	1.5
	3	6.5	12.5	.8	7.0	4.7	1.0	1.7
	4	7.1	14.0	.9	7.7	5.4	1.1	1.9
Type 3 River; LF = 0.1								
5	1	15.4	23.4	2.7	3.7	17.0	1.8	1.3
	2	24.3	38.2	4.8	4.2	29.3	2.8	1.7
	3	30.7	57.7	9.3	5.1	43.4	4.3	2.8
	4	29.6	80.9	17.6	6.4	56.8	5.9	4.8
8	1	17.5	33.5	5.5	3.9	24.1	2.6	2.2
	2	27.8	55.6	9.5	4.3	41.8	4.2	3.0
	3	29.1	83.2	18.5	5.8	58.9	6.1	5.0
	4	27.7	130.4	35.2	7.7	87.4	9.6	8.0

Table 3: Continued

Diversion No.	Depth	Ca	ΣCations	Cl	Alkalinity	SO_4	EC[1]	SAR[2]
			Type 3 River; LF = 0.4					
5	1	17.6	24.3	2.3	3.6	18.5	1.8	1.0
	2	22.5	31.4	3.0	4.1	24.2	2.3	1.2
	3	28.0	39.1	3.8	4.8	30.6	2.9	1.3
	4	32.0	44.8	4.4	5.3	35.1	3.2	1.4
8	1	26.5	40.0	4.6	3.4	32.0	2.9	1.6
	2	31.0	48.7	6.1	4.0	38.6	3.6	2.0
	3	31.1	53.4	7.6	5.0	40.8	4.0	2.4
	4	31.1	56.8	8.8	5.7	42.3	4.2	2.7

[1] EC is electrical conductivity in millimhos/cm.

[2] $SAR = Na/\sqrt{Ca^{2+} + Mg^{2+}/2}$

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in Table 4. For the Type 1 river with low leaching, some of the Ca and HCO_3 applied to the soil in the irrigation water precipitated in the soil as $CaCO_3$. Precipitation increased downstream, ranging from 329 to 5,600 metric tons per project.

Removal of salt from the river through nine diversions by this process totaled 21,000 metric tons. With high leaching management, however, $CaCO_3$ was dissolved from the soil by the irrigation water and discharged in the drainage water. This removal of $CaCO_3$ from the soil decreased downstream, ranging from 16,000 to 4,400 metric tons per project. For the entire river system, 78,000 metric tons of $CaCO_3$ were removed from the soil. This salt was returned in the drainage water and acquired by the river. The drainage water could maintain this increased level of $CaCO_3$ because of the relatively high level of CO_2 in the soil system. Upon mixing the drainage water with the undiverted river and exposure there to the lower CO_2 concentration of the surface water, the solubility of $CaCO_3$ in the river was exceeded after the third project and $CaCO_3$ precipitated within the river. The extent of this precipitation ranged between 13,000 and 19,000 metric tons per project. The accumulative loss of $CaCO_3$ from the river totaled 100,000 metric tons after nine diversions. Thus, with low leaching, $CaCO_3$ was removed from the river by deposition in the soil; with high leaching, $CaCO_3$ was removed from the river by deposition in the river channel. Eventually the total loss of $CaCO_3$ became the same for either leaching condition as the river water composition approached $CaCO_3$ saturation. But at any project before the ninth, the

Table 4: Net Metric Tons of Salt (x 10^{-3}) Precipitated or Dissolved (-) in Each Project

	Type 1: River Leaching Fraction = 0.1			Type 1: River Leaching Fraction = 0.4		
River Diversion	$CaCO_3$ in Soil	$CaCO_3$ in River	Total for River System	$CaCO_3$ in Soil	$CaCO_3$ in River	Total for River System
1	- 151	-	- 151	-20,780	-	- 20,780
2	329	-	329	-16,210	-	- 16,210
3	905	-	905	-11,360	-	- 11,360
4	1,461	-	1,461	- 6,340	13,330	6,990
5	2,071	-	2,071	- 4,860	18,830	13,970
6	2,840	-	2,840	- 4,900	18,270	13,370
7	3,655	-	3,655	- 4,860	17,960	13,100
8	4,616	-	4,616	- 4,690	17,410	12,720
9	5,631	-	5,631	- 4,400	14,870	10,470
Σ	21,357	-	21,357	-78,400	100,670	22,270

	Type 2: River Leaching Fraction = 0.1			Type 2: River Leaching Fraction = 0.4		
River Diversion	$CaCO_3$ in Soil	$CaCO_3$ in River	Total for River System	$CaCO_3$ in Soil	$CaCO_3$ in River	Total for River System
1	9,860	-	9,860	- 6,470	15,000	8,530
2	10,300	1,980	12,280	- 5,630	19,800	14,170
3	10,500	3,460	13,960	- 5,690	19,900	14,210
4	10,500	3,700	14,200	- 5,810	20,000	14,190
5	10,500	3,400	13,900	- 5,990	20,100	14,110
6	10,400	3,700	14,100	- 6,230	20,000	13,770
7	10,500	3,700	14,200	- 6,470	20,700	14,230
8	10,500	3,830	14,330	- 6,890	21,100	14,210
9	10,500	4,010	14,510	- 7,620	22,200	14,580
Σ	93,560	27,780	121,300	-56,800	179,000	122,200

Table 4 Continued

Type 3: River Leaching Fraction = 0.1

River Diversion	$CaCO_3$ in Soil	Gypsum in Soil	$CaCO_3$ + Gypsum in Soil	$CaCO_3$ in River	Net for River
1	10.3	46.1	56.4	26.7	83.1
2	7.2	49.2	56.4	3.5	59.9
3	7.1	52.6	59.7	3.0	62.7
4	7.0	56.5	63.5	3.0	66.5
5	6.8	60.8	67.6	3.4	71.0
6	6.6	65.8	72.4	3.2	75.6
7	6.4	71.8	78.2	3.5	81.7
8	6.1	79.1	85.2	3.5	88.7
9	5.7	89.2	94.9	4.1	99.0
Σ	63.2	571.1	634.3	53.9	688.2

Type 3: River Leaching Fraction = 0.4

River Diversion	$CaCO_3$ in Soil	Gypsum in Soil	$CaCO_3$ + Gypsum in Soil	$CaCO_3$ in River	Net for River
1	- 1.7	-	- 1.7	39.4	37.7
2	- 6.1	-	- 6.1	17.8	11.7
3	- 6.1	-	- 6.1	16.4	10.3
4	- 6.1	-	- 6.1	17.0	10.9
5	- 6.1	-	- 6.1	17.0	10.9
6	- 6.8	88.2	31.4	16.5	47.9
7	- 7.6	82.4	74.8	17.0	91.8
8	- 8.6	130.8	122.2	17.5	139.7
9	-10.3	186.3	176.0	18.6	194.6
Σ	-59.4	437.7	378.3	177.2	555.5

accumulative loss of salt from the river was greater under low leaching and, hence, the river salinity was lower, as shown in Table 2. This difference in salt concentration is of little practical consequence when assessing the suitability of this relatively pure water for irrigation.

More $CaCO_3$ was deposited in the soil with low leaching for the Type 2 river than for the Type 1 river. The amount was nearly the same in each project (about 10,400 metric tons). But, $CaCO_3$ was also precipitated from the Type 2 river after return and equilibration of the drainage water with the river, because the river was initially saturated with $CaCO_3$ and could hold no more. With high leaching, all the $CaCO_3$ that was removed from the soil was subsequently deposited in the river channel (since the river was initially saturated with $CaCO_3$). Hence the salt loads and river compositions were the same for both low and high leaching systems. The only difference between the two systems was the location of $CaCO_3$ deposition. With low leaching, $CaCO_3$ was deposited primarily in the soil (93,000 metric tons), with less in the river channel (28,000 metric tons). With high leaching, additional $CaCO_3$ was removed from the soil (57,000 metric tons). This amount of $CaCO_3$, together with $CaCO_3$ present in the original river load, subsequently precipitated in the river channel (179,000 metric tons).

With the Type 3 river, considerably more salt was removed from the river and deposited in the soil with low leaching than was the case for the other river types, primarily because of the precipitation of gypsum (Tab. 4). This deposition increased downstream, ranging from 56,000 to 95,000 metric tons per project and totaling 634,000 metric tons. With high leaching, $CaCO_3$ was removed from the soil in all projects. This removal increased downstream ranging from about 6,100 to 10,000 metric tons. In total 59,000 metric tons were removed from the soil and added to the water along the river system. Gypsum did not precipitate in the soil until the sixth project; its precipitation then rapidly increased from 38,000 to 186,000 metric tons, for a total of 437,000 metric tons. With low leaching about 6,500 metric tons of $CaCO_3$ were deposited in each project, totaling 63,000 metric tons for the river system. Gypsum similarly precipitated in each project, increasing downstream from about 46,000 to 89,000 metric tons per project and totaling 571,000 metric tons for the river system. It should be noted that more salts are precipitated in the soil below the seventh project with high leaching than with low leaching, because less salt had been removed upstream with high leaching. Hence when the river eventually became sufficiently concentrated in Ca and SO_4 downstream (by further consumptive use of the water) to exceed the solubility of gypsum, large amounts were there to precipitate. Some salt, about 3,200 metric tons per project, was also deposited in the river after drainage return with low leaching. About 17,000 metric tons of $CaCO_3$ per project were precipitated in the river with high leaching. At any project along the river the accumulative loss of salt was greater for low leaching, which resulted in lower river salinity under this management system (Tab. 2).

The total amount of salt deposited in or removed from the soil (including that salt dissolving from the soil in the upper profile and subsequently depositing in the lower profile) by quarter intervals is given in Table 5. For the Type 1 and 2 rivers, $CaCO_3$ deposition within the root zone quarters totaled about 8,000 and 15,000 metric tons per project with high and low leaching, respectively. Considerably more salt (gypsum as well as $CaCO_3$) was deposited in the soil root zone for the Type 3 river. With low leaching, the deposition increased downstream, ranging from 58,000 to 100,000 metric tons per project. With high leaching about 6,000 metric tons precipitated in each project through the fifth, thereafter precipitation increased rapidly from 43,000 to 188,000 metric tons. With all waters, $CaCO_3$ deposition was maximum in the second soil quarter, decreasing below; no $CaCO_3$ precipitated in the first quarter. For Type 1 and 2 rivers the proportion of $CaCO_3$ deposition was approximately in the ratio 2:1.5:1 for the second, third, and fourth soil intervals, respectively. For the Type 3 river the corresponding ratio was approximately 2.7:1.8:1. The actual values for a given river would depend on the water uptake and CO_2 distributions chosen, but the trends would be similar.

Gypsum precipitated in all projects in the third and fourth soil quarters with low leaching. The amount in the fourth quarter was about 30,000 metric tons in all projects. (This was also true for the high leaching condition after the fifth project.) The amount of salt precipitating in the third quarter increased in each project downstream ranging from about 15,000 to 60,000 metric tons. With high leaching, precipitation of gypsum began after project five. Gypsum precipitated in the second quarter in the eighth and ninth projects (34,000 and 90,000 metric tons, respectively). Precipitation in the third quarter was about 50,000 to 65,000 metric tons. After the sixth project, total salt deposition in the soil was greater with high leaching than with low leaching for the Type 3 river.

Salt is deposited in the soil even with high leaching because $CaCO_3$ is dissolved in the upper quarters and is deposited in the lower quarters, even though there is no net deposition in the soil with respect to that derived from the irrigation water per se. For the Type 1 and 2 rivers, the increase in amount of deposition in the third quarter of the soil root zone was about 3,000 metric tons per project more with low than with high leaching. The irrigated area of each project was 10,100 hectares (25,000 acres). If the original bulk density of the soil were 1.47 g/cc, and the specific gravity of the precipitated $CaCO_3$ is 2.65, the porosity would be reduced about 0.008% more per year with low than with high leaching. For the Type 3 river, a similar increased reduction in porosity would result from $CaCO_3$ deposition with low leaching. In addition, gypsum also precipitated in the soil from this river. Above the eighth project this precipitation was typically about 30,000 metric tons per project (about ten times the amount of $CaCO_3$ deposition). Based on the above assumptions and assuming that the specific gravity of gypsum is 2.35 g/cc, gypsum deposition would reduce porosity about 0.08% more per year with low leaching. This loss of porosity should

Table 5: Precipitation of salts in the soil. Values are in metric tons (x10^3) per quarter depth per project in the root zone includes in situ dissolution and subsequent precipitation.

		Type 1			Type 2		
Diversion	Quarter Depth	LF = 0.1 $CaCO_3$	LF = 0.4 $CaCO_3$	$\Delta CaCO_3$	LF = 0.1 $CaCO_3$	LF = 0.4 $CaCO_3$	$\Delta CaCO_3$
2	1	-15.01	-24.39	9.38	-5.49	-13.67	8.18
	2	6.74	4.40	2.34	6.88	4.38	2.50
	3	5.35	2.53	2.82	5.47	2.41	3.06
	4	3.25	1.25	2.00	3.49	1.26	2.23
5	1	-13.04	-12.98	- .06	-5.49	-14.02	8.53
	2	6.72	4.39	2.33	6.86	4.46	2.40
	3	5.28	2.49	2.79	5.52	2.40	3.12
	4	3.11	1.25	1.86	3.57	1.18	2.39
9	1	- 6.72	-11.96	5.2	-6.23	-15.4	9.17
	2	6.16	4.11	2.01	7.0	4.35	2.70
	3	4.26	2.23	2.03	5.83	2.29	3.54
	4	1.93	1.18	.75	3.85	1.14	2.71

		Type 3					
		LF = 0.1		LF = 0.4		LF = 0.1-0.4	
Diversion	Quarter Depth	$CaCO_3$	Gypsum	$CaCO_3$	Gypsum	$\Delta CaCO_3$	$\Delta CaSO_4$
2	1	-5.14	0	-12.82	0	7.73	0
	2	5.97	0	3.84	0	2.13	0
	3	4.18	18.63	1.94	0	2.24	18.63
	4	2.22	30.58	.99	0	1.23	30.58
5	1	-5.22	0	-12.3	0	7.08	0
	2	5.91	0	3.44	0	2.47	0
	3	3.94	30.65	1.83	0	2.11	30.65
	4	2.21	30.19	.92	0	1.29	30.19
9	1	-5.75	0	-11.95	0	6.20	0
	2	6.08	1.57	1.60	89.63	4.48	-88.06
	3	3.12	59.92	.19	64.29	2.93	- 4.37
	4	2.25	27.72	.13	32.42	2.38	- 4.70

not be detrimental. The salts should deposit at the point where they are concentrated, near the root hairs, which are distributed throughout the soil mass. Thus, the depositional pattern should be diffuse and should be different from year to year, and plugged strata or pans would not be expected. Concern about the effects of clogging by salt precipitation does not appear to be a serious consideration.

DISCUSSION

In previous work, it was shown that the amount of salt discharged from a soil profile can be significantly reduced with reduced leaching irrespective of river water composition. Although this occurs, the reduced salt load in the return flow may or may not reduce the salt load of the river water. It is the successive mixing and readjustment to lower CO_2 levels of the return flows and the type of irrigation water that determine if lower leaching will result in reduced salt loads in the river system. Reduced leaching will result in reduced volumes of return flow. This may make it feasible to intercept and dispose of it by means other than returning it to the river. Of course in this case the salt load volume and concentration of the river system would be reduced by the amount of salt diverted in the irrigation water but the salt concentration of the river would remain unchanged. Reduced leaching in this case means less water diverted, salt precipitation and storage in the soil profile, and increased salt concentration in the drainage water. This may or may not be desirable with respect to local ground water supplies.

In the above analysis the only source of salt inputs considered was $CaCO_3$ dissolution. As previously mentioned changes in irrigation management (to high efficiency) could result in additional changes. Actual river systems associated with irrigated lands receive salt inputs from sources whose compositions are affected by processes other than evapotranspiration. Saline ground waters are often mixed with or displaced by the irrigation drainage waters so that the river receives larger salt inputs than would be expected if an equivalent amount of irrigation drainage water were returned to the river. Raising of the water table under high leaching can result in dissolution of saline minerals in the previously unsaturated zone and evaporation of water from the water table (thereby further increasing salinity as well as requiring additional costly drainage control). An assessment of benefits in any basin requires an analysis of the particular characteristics of that basin and a decision on priorities. Very dilute waters such as Type 1 waters would be reduced in salinity downstream under low or high leaching. For downstream municipal users the reduction in water hardness would be beneficial, but this would probably not be true for downstream agriculturalists. In fact they might benefit from additions of amendments (such as $CaSO_4$, $CaCl_2$ or H_2SO_4 or SO_2) to increase their Ca levels to improve infiltration rates. Other basins, particularly those undergoing urbanization, that are presently overdrafting ground water could benefit from high leaching if this agricultural water was a net addition of water to the basin. A particular case would be use of treated municipal wastewater for irrigation of new lands and recharge of ground water, assuming the municipal water was considerably lower in salinity than that presently in the basin.

This investigation was primarily an analysis of the potential effects of changes in irrigation management per se on downstream river and soil water compositions. We assumed no addition of salts other than dissolution of $CaCO_3$ to enable a generalized analysis. For any specific system the input of additional salts is often important and must be evaluated. In general these additional considerations favor minimized leaching with optimum utilization of the undiverted water for other purposes.

CONCLUSIONS

1. Rivers undersaturated with $CaCO_3$ experienced net removal of $CaCO_3$ from solution under low leaching and a net dissolution of $CaCO_3$ under high leaching.

2. Rivers saturated with $CaCO_3$ lost $CaCO_3$ by precipitation in the soil rootzone under low leaching and by precipitation of $CaCO_3$ in the river channel (after remixing the drainage water with the undiverted river water) under high leaching. The total amounts of precipitation and the river compositions were unaffected by irrigation management.

3. Rivers saturated with $CaCO_3$ and nearing saturation with gypsum lost substantially more salts by precipitation under low versus high leaching. Precipitation of salts was relatively constant through successive valleys under low leaching. Under high leaching, initial valleys had no gypsum precipitation but subsequent valleys showed a sharp rise in precipitation. Total precipitation in the last valley was higher under high leaching than under low leaching.

4. In all instances, calcium was redistributed by dissolution from the upper portion of the soil profile and reprecipitation in the lower portion.

5. For $CaCO_3$-saturated rivers, the reduction in soil porosity was about 0.008% more per year under low vs. high leaching.

6. For rivers that result in precipitation of gypsum in the soil, porosity was reduced about 0.08% more per year for low as compared to high leaching.

REFERENCES

Oster, J. D., and J. D. Rhodes. 1975. Calculated drainage water compsitions and salt burdens resulting from irrigation with river waters in the Western United States. J. Environ. Qual. 4:73-79.

Rhoades, J. D., and L. Bernstein. 1971. Chemical physical, and biological characteristics of irrigation and soil water. In L. L. Ciaccio, ed., Water and Water Pollution Handbook, Marcel Dekker, Inc., New York. Vol. I:141-222.

Rhoades, J. D. 1972. Quality of water for irrigation. Soil Sci. 113: 277-284.

Rhoades, J. D., R. D. Ingvalson, J. M. Tucker, and M. Clark. 1973. Salts in irrigation drainage waters. I. Effects of irrigation water composition, leaching fraction, and time of year on the salt composition of irrigation and drainage waters. Soil Sci. Soc. Amer. Proc. 37:770-774.

Rhoades, J. D., J. D. Oster, R. D. Ingvalson, J. M. Tucker, and M. Clark. 1974. Minimizing the salt burdens resulting from irrigation with river water in the western United States. J. Environ. Qual. 3:311-316.

Rhoades, J. D., and S. D. Merrill. 1975. Assessing the suitability of water for irrigation: Theoretical and empirical approaches. Proc., Expert Consultation on Prognosis of Salinity and Alkalinity, FAO Soils Bull. 31:69-109.

U. S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. In L. A. Richards, ed., USDA Agr. Handbook No. 60. 160 p.

Van Schilfgaarde, J., L. Bernstein, J. D. Rhoades, and S. L. Rawlins. 1974. Irrigation management for salt control. J. Irrig. and Drainage Div., ASCE, 100 (IR 3), Proc. Paper 10822, pp. 321-338.

WATER QUALITY AND RETURN FLOW STUDY OF THE OAHE UNIT, SOUTH DAKOTA

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INTRODUCTION

The Oahe Unit will provide irrigation water from the Missouri River for 190,000 acres (77,000 has) of land in the James River Valley of South Dakota. Return flows from this irrigation will accrue to the James River, affecting both the quantity and quality of its flow. The Bureau of Reclamation has conducted a series of studies to predict the quality, quantity, and timing of these return flows and to evaluate the effects of this water upon the river and the continued beneficial use of its resultant flow.

Scope

The primary tools used in these studies of the Oahe Unit were a return flow simulation model and a routing model developed by the Bureau of Reclamation for detailed study of irrigation return flows. This paper will discuss the Oahe Unit, its plan of operation, application of the return flow model to the Unit, routing of those return flows into and through the James River within the project area, and the resulting flow of the river.

Background

Prior to 1973, several studies of Oahe Unit return flows had been conducted for planning and design of the project. Those early studies were based upon the salt balance procedure for estimating the salinity and constituents of irrigation return flows. While this method produced good estimates of ultimate levels of return flow salinity from the project, it did not show the development of the equilibrium condition and the leaching of materials from soils of the Unit.

Early in 1973, the Missouri-Oahe Projects Office began collection of field data for a new return flow study of the Oahe Unit. Soil master sites were located to represent lands that would be irrigated with water from the project. Those soils data, along with other data on the project, climate, crops, ground water, drainage, streamflow, etc., were gathered and submitted to the Bureau of Reclamation's

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[1] Colorado River Water Quality Office. U.S. Bureau of Reclamation. Engineering and Research Center, Denver, Colorado.

Engineering and Research Center for processing with the return flow simulation model.

The return flow simulation model represents the state of the art in predicting deep percolation return flows from irrigation. The model is based upon the "salt pickup" principle, and its development represented a joint effort between the Bureau of Reclamation and Dr. Gordon Dutt of the University of Arizona. The main functions of the model are to simulate a soil profile with all available data, consider irrigation applications from beginning through the leaching process to establishment of equilibrium (salt balance stage), and predict the quantity, quality and timing of deep percolation from the area. These results were then fed into a companion routing model for mixing with canal seepages, operational wastes and streamflows of the area and predicting constituent levels and flows at several points along the James River.

This study of Oahe Unit return flows was completed in September 1975 and resulted in the release of a draft report entitled "Summary Report, Water Quality and Return Flow Study, Initial Stage Oahe Unit." It should be remembered that results from simulated return flow studies are estimates of conditions that may be expected under project operation. It is impossible to predict exact flow and quality levels for drain effluent from an irrigated area.

THE OAHE UNIT AND THE JAMES RIVER

Oahe Unit

The Oahe Unit is part of the Pick-Sloan Missouri Basin Program for development of water resources in the Missouri River Basin. The Initial Stage of the Oahe Unit was authorized by Public Law 90-453 in August 1968. Its principal purposes are to furnish a surface irrigation water supply for approximately 190,000 acres (77,000 has) of land provide water for municipal uses, conserve and develop fish and wildlife resources, enhance outdoor recreation opportunities, and reduce flood damage. The development of the Unit will provide for diversion, storage, and delivery of Missouri River water from Lake Oahe to the James River Basin.

Oahe Unit irrigation will be concentrated on the West and East Lake Plains of the James River Valley. Principal features for delivering water to these lands include the Oahe Pumping Plant, 214 miles (344 km) of main supply canals, three major regulating reservoirs, 955 miles (1537 km) of small canals and laterals, 935 miles(1505 km) of open drains, and 2,970 miles (4780 km) of closed drains. Figure 1 illustrates the general supply features of the unit and shows the geographical layout of the system.

As presently proposed, development of the 190,000 irrigable acres (77,000 has) in the James River Valley will be accomplished over a 13-year period, beginning in the early 1980's. The areas in the valley most directly affected by water supply and irrigation aspects of the project are the South Dakota counties of Brown, Spink and Beadle.

James River

The James River above Huron drains a predominantly agricultural area of about 16,800 square miles (43,500 km^2) in North and South Dakota. Precipitation within the basin averages over 17 inches (430 mm) annually, but only about 1/4 inch (4 mm) arrives at Huron as runoff. The section of the river evaluated in return flow studies extends from Columbia to Huron, South Dakota. In this section, the James River is a prairie-type stream with large meanders and an average slope of about 4 inches per mile (6 cm/km).

Historic flows of the James River range from very high, usually occurring during the flood period from March through June, to extended periods of no flow. The maximum flow on record for the river at Huron is 9,000 ft^3 (255 m^3)/s which occurred April 13, 1969. A flow of this magnitude is normally expected once in 100 years.

The average streamflow of the James is about 260 ft^3 (7.3 m^3)/s. The median streamflow is 120 ft^3 (3.4 m^3)/s, which reflects the low flow characteristics of the river.

Minimum flows in the river are usually observed during the late summer and winter months. Historically at Huron, the conditions are:

a. No flow approximately 20 percent of the time, and

b. An average flow of only 25 ft^3 (0.7 m^3)/s during September through February.

The present quality of James River streamflow is considered marginal at best. Raw water from the river must undergo extensive treatment before it is suitable for public consumption. The City of Huron does, however, rely on the James River as its principal source of water, primarily because of no adequate alternative water supply.

Review of water quality constituent concentrations of historic James River streamflows shows a wide range of variation. Maximum constituent concentrations usually occur during the winter months when flow is at a minimum. Minimum constituent concentrations usually occur during flood periods (March through June) when flows are at a maximum. At Huron, the maximum TDS concentration exceeded 1,900 mg/l in March 1965 during low streamflow. The minimum observed TDS level was 147 mg/l in April 1960, when streamflow averaged 5,800 ft^3 (162 m^3)/s The average TDS concentration for the James River at Huron from 1957 through 1972 was 787 mg/l. Water quality data were not collected on a continuous basis prior to 1957.

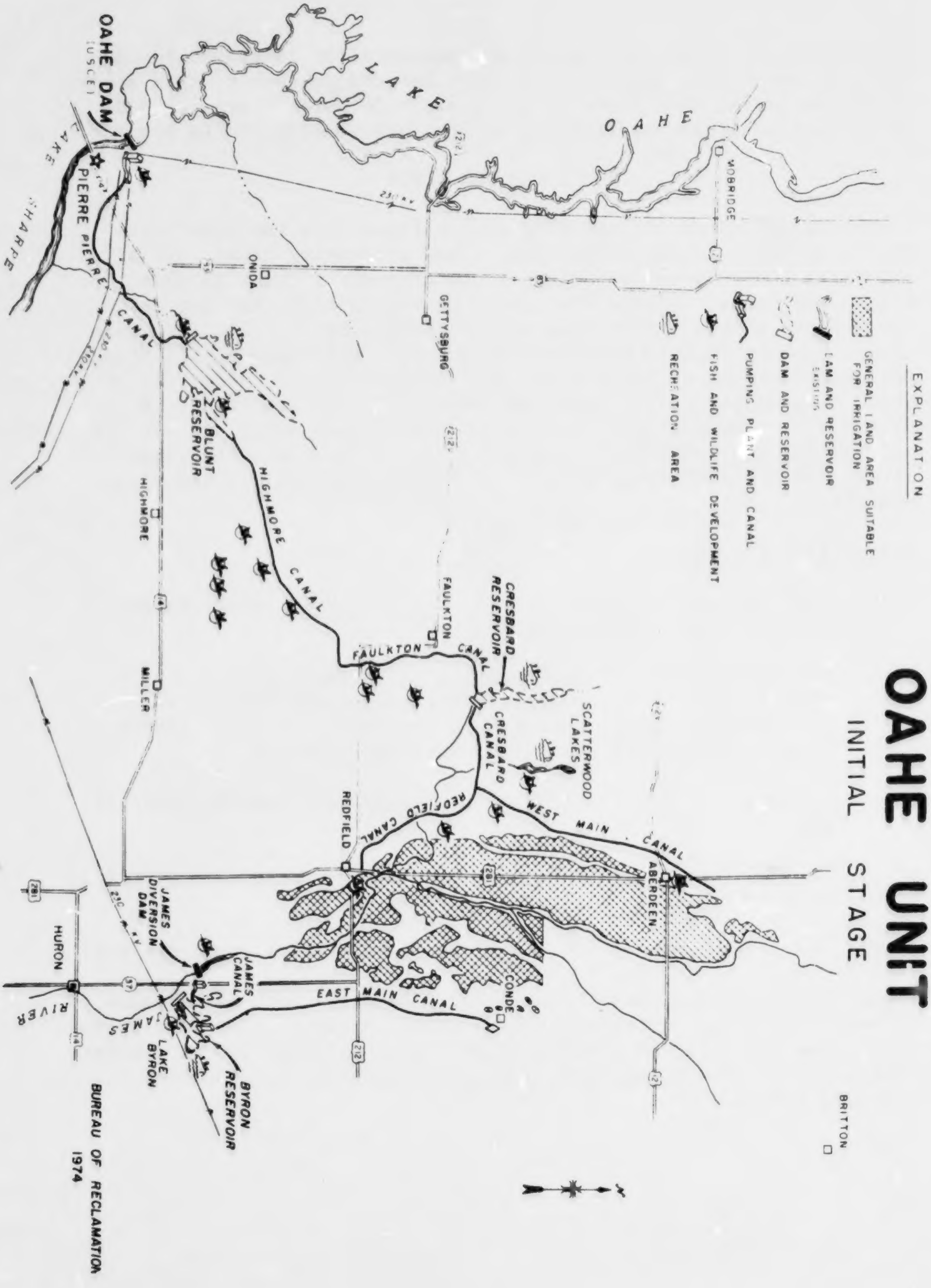
Plan of Operation

Water supply for the Oahe Unit will be pumped from the Missouri River by the Oahe Pumping Plant. Conveyed by the Pierre Canal to Blunt Reservoir, the water will be regulated for delivery by Highmore and Faulkton Canals to Cresbard Reservoir. Cresbard Canal will then make the water available to the West Main and Redfield Canals for delivery to the irrigable areas. Figure 1 is a general area map of these facilities showing their relationship with each other.

Water for the irrigation of 125,000 acres (50,600 has) in the West Lake Plain area (the irrigable area of glacial Lake Dakota on the west side of the James River) will be delivered directly to those lands by the West Main Canal and its lateral system. Return flows from that irrigation will be collected by drains and discharged into the James River.

Water for the irrigation of 65,000 acres (26,000 has) in the East Lake area will be supplied from the Missouri River and Oahe Unit return flows. Return flows from the West Lake Plain and East Lake Plain areas of the project will be collected by the James River, augmented with project water from Redfield Canal, diverted by the James Diversion Dam and Canal to Byron Reservoir for regulation, and pumped into the East Main Canal for delivery to East Lake Plain irrigable areas. Natural flow of the James River will be mixed with Oahe Unit return flows and project water releases, but the quantity of flow downstream of James Diversion Dam will not be reduced except during flood flow periods. During the irrigation season, TDS levels of the James River will be maintained below 1,000 mg/l.

The method of irrigation water application in the Oahe Unit will be the landowner's choice. The Lake Plain is well suited for gravity


EXPLANATION
GENERAL LAND AREA SUITABLE FOR IRRIGATION
DAM AND RESERVOIR EXISTING
DAM AND RESERVOIR
PUMPING PLANT AND CANAL
FISH AND WILDLIFE DEVELOPMENT
RECREATION AREA
LAKE OAHE
OAHE DAM (USCE)
LAKE SHARPE
PIERRE
PIERRE CANAL
ONIDA
GETTYSBURG
MOBRIDGE
BLUNT RESERVOIR
HIGHMORE
HIGHMORE CANAL
FAULKTON
FAULKTON CANAL
CRESBARD RESERVOIR
CRESBARD CANAL
SCATTERWOOD LAKES
MILLER
REDFIELD
REDFIELD CANAL
WEST MAIN CANAL
ABERDEEN
JAMES DIVERSION DAM
JAMES CANAL
EAST MAIN CANAL
CONDE
HURON
JAMES RIVER
LAKE BYRON
BYRON RESERVOIR
BRITTON
212
281
14
12
37
83

OAHE UNIT
INITIAL STAGE

BUREAU OF RECLAMATION
1974

application of water, but sprinkler systems offer considerable convenience and better control of water. For the purpose of this study, it was estimated that there would be about 50 percent gravity and 50 percent sprinkler application of irrigation water in the project.

PROCEDURE FOR STUDY

The basic procedure for studying return flows from the Oahe Unit was to define existing water quality and streamflow conditions of the James River Basin, superimpose the proposed irrigation upon those conditions, compute the resulting return flow, and determine the effects of the return flow upon the James River. The five main steps involved in this procedure were: (1) definition of the study and establishment of constraints and assumptions, (2) gathering of basic data on the basin, river, and Oahe Unit, (3) analyzing the data with a computer model to predict return flow quantity, quality, and timing, (4) routing the resulting return flow into the James River, and (5) evaluating results of the routing and effects upon the river.

Return Flow Components

The "total" return flow considered in the Oahe Unit investigation was a combination of the following elements:

a. Deep percolation - Water applied as irrigation delivery which infiltrates the farm fields and passes through the soil system before returning to the surface outlet, either through natural or artificial drainage pathways.

b. Seepage - From project distribution system (canals, laterals, etc.).

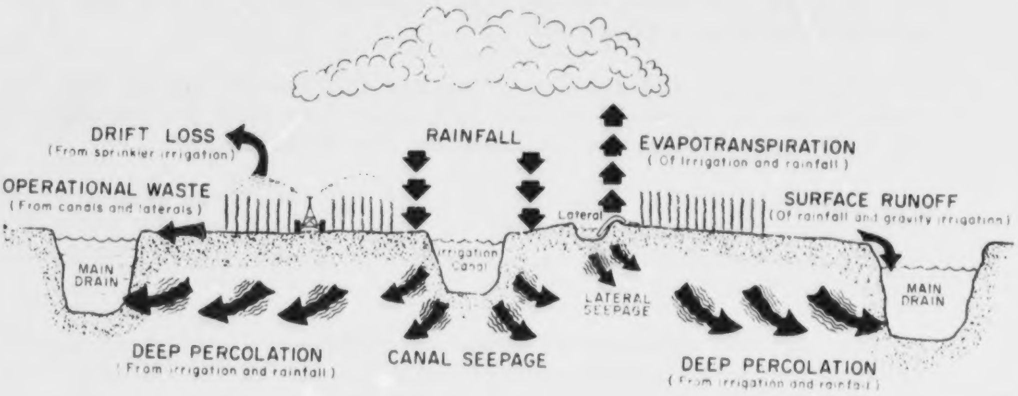
c. Farm surface runoff - Runoff from fields that occurs naturally with most gravity methods of irrigation.

d. Operational wastes - From project canals and lateral systems.

Figure 2 illustrates these return flow elements. Each was considered in detail in Oahe Unit return flow studies, although only deep percolation was predicted by model studies. Estimates for the others were obtained from project designs, irrigation experience, and other reliable sources.

Figure 2

DEVELOPMENT OF RETURN FLOWS
From irrigation in the Oahe Unit


DRIFT LOSS
(From sprinkler irrigation)
RAINFALL
EVAPOTRANSPIRATION
(Of irrigation and rainfall)
OPERATIONAL WASTE
(From canals and laterals)
Lateral
SURFACE RUNOFF
(Of rainfall and gravity irrigation)
MAIN DRAIN
Irrigation Canal
LATERAL SEEPAGE
MAIN DRAIN
DEEP PERCOLATION
(From irrigation and rainfall)
CANAL SEEPAGE
DEEP PERCOLATION
(From irrigation and rainfall)

Modeling Assumptions

In studying return flows from irrigation of the Oahe Unit, several assumptions and restrictions were necessary to apply return flow models to the system and adequately represent conditions that may be expected. The most important of these assumptions are as follows:

1. An operational irrigation management service program will be used on the Oahe Unit to assist farmers in determining the proper timing and quantity of irrigation applications.

2. About 50 percent of Oahe Unit lands will be irrigated with gravity systems and about 50 percent will be irrigated with sprinkler systems.

3. Full development of irrigation in the Oahe Unit will take about 13 years. West Lake Plain development will be attained at the end of the ninth year after water delivery begins, and full West and East Lake Plains development will be achieved at the end of the thirteenth year.

4. During the operating season (April through October), sufficient project augmentation water will be discharged to the James River

to maintain TDS levels of its streamflow below 1,000 mg/l (current South Dakota Water quality standards for that reach of the river).

5. No augmentation water will be released during the winter months (November through March).

6. The quantity and quality of return flows accruing to the James River as a result of Garrison Diversion Unit irrigation in North Dakota were not included in the modeling.

7. The average root zone for crops of the Oahe Unit area will be approximately 3 feet (0.9 m) deep. Therefore, the water level in irrigated fields will be maintained at least 3 feet (0.9 m) below the ground surface.

8. The lateral operational waste to the James River is directly related to the irrigated acreage being served in the various blocks of land. The main canal operational waste to the James River will be directly related to the number of acres to be served from either the West Main Canal or the Redfield Canal.

Of course, many other assumptions were involved in studying return flows from the Oahe Unit. They will be discussed in the following sections as they become pertinent.

Basic Data

As in all model studies, results from the investigation of Oahe Unit irrigation return flows are only as good as the data chosen to mathematically represent conditions (current and expected) in the project area. Great care was taken in selecting representative data to characterize the many varied conditions and parameters of the James River Valley, the Oahe Unit, and operation of the project.

Soil conditions of irrigable lands in the Oahe Unit were represented within the project area through a "master site" concept, where similar soil conditions of an area were related to detailed chemical and physical analyses of samples from a master site chosen to represent that area. A total of 21 master sites were selected to represent the soil types and chemistry of the 190,000 acres (77,000) of the project. The selection of these master sites was based on soil profile data and detailed soil analyses of 11,500 test holes which are located on the irrigable lands within the Lake Plain area.

The master site concept was also utilized to represent drainage characteristics of Lake Plain area lands. A total of 110 investigational borings were made in the project area and determinations of specific yield, permeability, depth to barrier, and water-holding capacity were made for each boring. The respective bore holes were then related to each of the 21 soil master sites and average drainage characteristics were computed for each.

Data for ground water now present in the Oahe Unit area were incorporated into the study from data obtained from 29 U.S. Geological Survey observation wells. These data provided the depth to ground water and chemical quality at each well.

It was assumed that the total dissolved solids (TDS) concentration of Missouri River water will average 450 mg/l as it is removed from the river at Oahe Pumping Plant. Storage of this water in Blunt and Cresbard Reservoirs will concentrate the TDS to 488 mg/l as the water enters Cresbard Canal for subsequent delivery to the Lake Plain area. The individual constituent concentrations of this water are tabulated below:

Constituent	Average Concentration (mg/l)
Calcium	50
Magnesium	19
Sodium	58
Chloride	9
Sulfate	164
Bicarbonate	187
Carbonate	0
Nitrate	1

Average weighted crop data were utilized to include the effects of a cropping pattern on return flow water quality. The typical crop pattern was comprised of corn grain (44 percent), corn silage (7 percent), sugar beets (16 percent), small grain (11 percent), alfalfa (13 percent), and pasture (9 percent). Other crop data were planting and harvest dates, full cover dates, soil freeze and thaw dates, etc.

Climatic data were also important to the modeling process, especially in computations of crop consumptive use. Temperatures, rainfall, solar radiation, freeze dates, and growing season length data were obtained from weather stations in the project area.

To develop a mathematical model of the James River system, a numerical representation of the stream flow characteristics over an extended period of years was needed. The study period was established to coincide with available quality data on the James River which has been collected on a continuous basis sine 1957. U.S. Geological Survey quantity and quality records for the period 1957-1972 were utilized in the study. To give a realistic simulation period, these 16 years of historic data were repeated or "folded over" three times resulting in a 48-year study period. It is realized that the 16 years of historic conditions will never be exactly repeated. However, the period does contain extreme conditions.

Return Flow Model

The Bureau of Reclamation's return flow model was developed by the Bureau of Reclamation's Engineering and Research Center and Dr. Gordon Dutt of the University of Arizona to predict the quantity, quality,and timing of return flows from irrigated lands that are drained by tile drainage systems. In accomplishing these predictions, the movement of irrigation water is traced through the soil system, starting at the soil surface and ending at the drain.

The return flow model treats both saturated and unsaturated flow hydraulics of the irrigation water in the soil column and provides a detailed balance of the chemical reactions and transformations (including solution, weathering of minerals, precipitation, ion exchange, and ion pairing) in the ground water and ground water system to give the quantity and quality of resulting return flow at the accrual points to drains from the irrigated areas. The model also involves the use of three other programs: an irrigation scheduling program to predict timing and amounts of irrigation; the saturated flow program that transfers ground water percolation to a drainage system; and a drainage system program that adjusts the output of the saturated flow program into a drainage outflow pattern. When combined, these programs and the model give results that include soil moisture contents, water levels, flow lines, drain discharge, the quality of soil water at the water table, and the quality of the drainage effluent. Quality predictions include estimates of TDS concentration and its primary constituents: calcium, magnesium, sodium, chloride, sulfate, bicarbonate, carbonate, ammonium, and nitrate.

Dr. Marvin J. Shaffer of our Hydrology Branch has discussed this return flow prediction model in more detail in another paper published in these symposium proceedings.

Mixing and Routing Model

Results from the return flow model application to the Oahe Unit were mixed with canal seepages and operational wastes and routed into the

James River. This portion of the modeling process was accomplished with another computer model specifically designed for the Unit and the James River.

The mixing and routing model has a nodal concept or structure, with a node representing a specific drainage area arbitrarily established for the study. The James River was divided into eight nodes for the major reaches of the river in the project area. Each node contained varying numbers of sequences - each sequence representing a specific inflow or outflow such as:

a. Inflow from previous node (always Sequence 1)

b. Tributary inflow

c. Inflow from Oahe Unit operation

d. Outflow from node

Each sequenced inflow resulting from Oahe Unit operation represented the "total" return flow (i.e., a combination of deep percolation, irrigation surface runoff, seepage losses, operational wastes, and any project releases which may have been made) accruing to the river at that point. Each of the Oahe Unit inflow areas were represented by specific combinations of master sites to cover irrigation conditions in the contributory area.

Operation of the model was conducted on a monthly basis in the direction of flow through the basin. For a specific month, historic streamflow and water quality data for the James River at Columbia (Node 1, Sequence 1) were read into the model, to this were added all of the sequenced inflows in Node 1 and the resultant flow and quality of the James River below Elm River (Node 1, Sequence 6) was generated. The outflow from Node 1 (James River below Elm River) is the inflow to Node 2. To this, the model added the sequenced inflows of Node 2 and generated the resultant streamflow and quality for the James River below Moccasin Creek. The outflow from Node 2 is the inflow to Node 3. Similarly, the model worked its way through all eight nodes for a specific month, proceeded to the next month, reset to Node 1, Sequence 1 and worked back through all eight nodes again.

For each month, the model incorporated the flow and quality of the various sequenced inflows and generated the total flow and resulting quality at the end of each of the eight nodes. The TDS as expressed by the model is the arithmetic sum of the calcium, magnesium, sodium, chloride, sulfate, bicarbonate, carbonate,and nitrate computed concentrations.

The model was structured such that once full West Lake Plain development was attained in water delivery year 9, the capability exists to augment the James River flows with up to 730 ft^3(20.7 m^3)/s of Missouri River water in any one month. Flow augmentation may be used for quality dilution (i.e., reduction of TDS through dilution) and/or quantity augmentation to supplement diversions to Byron Reservoir for subsequent irrigation of the East Lake Plain. During Byron Reservoir operation, the model expresses (on a monthly basis) the (a) quantity and quality of diversion from the river to the reservoir; (b) quantity and quality of releases from the reservoir to the East Lake Plain for irrigation; and (c) content and quality of the water remaining in the reservoir.

The node-sequence structure for the mixing and routing model allowed a tremendous flexibility in studying the James River system. It was possible to select any combination of node/sequence numbers to simulate various conditions. In this manner, the resulting study gives streamflow and water quality data at all major points along the river. Evaluation of Oahe Unit impacts were then much easier to locate and investigate.

RESULTS

The basic approach of this study of Oahe Unit irrigation return flows was to estimate return flow quantities and qualities, superimpose those return flows upon the existing James River system, and evaluate impacts of the development. Results from the study may be separated into two categories, one for the return flows and the other for resultant flows of the James River.

Results of the study are not to be misunderstood as an exact representation of conditions which will result under operation of the Oahe Unit. Rather, the results should be viewed as adequate for the planning of operation of the Unit and a representation of average and extreme conditions that can reasonably be expected to occur.

Return Flows

Return flows from the West Lake Plain area of the Oahe Unit will contribute about 178,000 acre-feet (219×10^6 m^3) of water annually to the James River. This water will accrue from the following sources:

	Acre-feet	Percent
Irrigation surface runoff from fields	11,750	6.6
Canal and lateral system operational wastes	24,460	13.8
Lateral and farm system seepage losses	35,250	19.8
Canal and reservoir seepage losses	60,560	34.0
Deep percolation-precipitation plus irrigation	45,930	25.8
Total	177,950	100.0

About 59,000 acre-feet (73×10^6 m^3) of return flow from the East Lake Plain area of the project will be discharged to the river and will consist of the following:

	Acre-feet	Percent
Irrigation surface runoff from fields	6,110	10.3
Canal and lateral system operational wastes	6,720	11.4
Lateral and farm system seepage losses	18,330	31.0
Canal and reservoir seepage losses	4,100	6.9
Deep percolation-precipitation plus irrigation	23,880	40.4
Total	59,140	100.0

The estimated average future quality of Missouri River water (TDS of 488 mg/l) was used to estimate the quality of the farm surface runoff. It was assumed that the total salt load of farm surface runoff would be retained in the return flow from this source.

The reduction in flow volume caused by nonproductive consumptive use within return flow channels would increase the concentration of the remaining water (11,750 acre-feet (14.5×10^6 m^3) from the West Lake Plain area and 6,110 acre feet (7.5×10^6 m^3) from the East Lake Plain) to 633 and 1,300 mg/l, respectively, by the time these flows reach the James River.

Seepage losses from the total distribution system were assumed to reflect a transient salt balance concept. The losses would initially raise the water table elevation under and near the canal alinement to establish a hydraulic gradient sufficient to move the water toward the nearest drain. The initial drainage outflow would be the resident local water, then mixtures of the resident and seepage waters, and finally the canal seepage water. For the quality of the return flow, it was assumed that this quality displacement would take 5 years for seepage losses from the laterals and farm systems and 3 years for the larger canals. The initial qualities were then estimated to be that of resident ground water (ranging from 1,580 to 6,000 mg/l TDS) at pertinent master sites for each of the areas. The final qualities by the salt balance concept would be the Missouri River water concentrated to 609 mg/l for the smaller laterals and 541 mg/l for the larger canals of the West Lake Plain area. Comparable figures for the East Lake Plain area are 1,250 mg/l for the smaller laterals and 1,111 mg/l for the larger canals.

Operational wastes were likewise assumed to retain their salt load. These wastes were concentrated from 488 to 541 mg/l in the West Lake Plain area.

The following table summarizes the annual volumes and associated TDS concentrations of the individual return flow waters during the 25th year of Oahe Unit operation.

	West Lake Plain Area		East Lake Plain Area	
Return Flow Water	Volume (ac-ft)	TDS Concentration (mg/l)	Volume (ac-ft)	TDS Concentration (mg/l)
Deep percolation-precip. plus irrig.	45,930	3,252	23,880	5,282
Irrigation surface runoff	11,750	633	6,110	1,300
Farm distribution seepage	9,400	609	4,890	1,250
Lateral seepage	25,850	642	13,440	1,318
Canal & reservoir seepage	60,560	541	4,100	1,111
Lateral operational wastes	12,930	664	6,720	1,364
Canal operational wastes	11,530	541	- 1/	-
Totals	177,950	1,274 2/	59,140	2,902 2/

1/ There will be no operational waste from the East Main Canal. Those losses will be wasted through the lateral system only.

2/ Volume weighted concentrations.

Resultant Flows of the James River

In considering the resultant flow of the James River with Oahe Unit return flows, it must be remembered that accruals from the West Lake Plain area may be reused on the East Lake Plain area and that augmentation water may be released to the river to assure compliance with South Dakota water quality standards during the operating season. Under preproject conditions, the average annual flow of the James River at Huron was 180,000 acre-feet (222×10^6 m^3) with a TDS concentration of 787 mg/l. Under post-Oahe Unit conditions, the average annual flow at Huron will be 327,000 acre-feet (403×10^6 m^3) with a TDS concentration of 1,096 mg/l. Figure 3 is a schematic representation of the Oahe Unit and composition of resultant James River streamflow at Huron.

To achieve compliance with South Dakota water quality standards during the operation season, approximately 37,760 acre-feet (47×10^6 m^3) of water must be released annually from the Redfield Canal to the James River. The following tabulation gives some detailed chemical characteristics of resultant streamflow at Huron:

Constituent	Pre-Project (1957-72) Average Concentration (mg/1)	Post-Project Average Concentration (mg/1)
TDS (residue)	787	1,096
Calcium	72	107
Magnesium	44	58
Sodium	133	175
Chloride	69	74
Sulfate	274	505
Bicarbonate	355	333
Carbonate	0.5	0

There will be no flow augmentation during the winter period (November through March). The TDS level of the James River during the nonoperating season will range from about 550 mg/l to 1,900 mg/l with an average of approximately 1,430 mg/l. Historically (1957-72), TDS concentration of James River streamflow has ranged between 361 mg/l and 1,906 mg/l with an average of 988 mg/l during that period.

CONCLUSIONS

The objective of the water quality and return flow study was to simulate operation of the Initial Stage Oahe Unit to obtain a reasonable estimate of the quantity and quality of return flows

OAHE UNIT SCHEMATIC

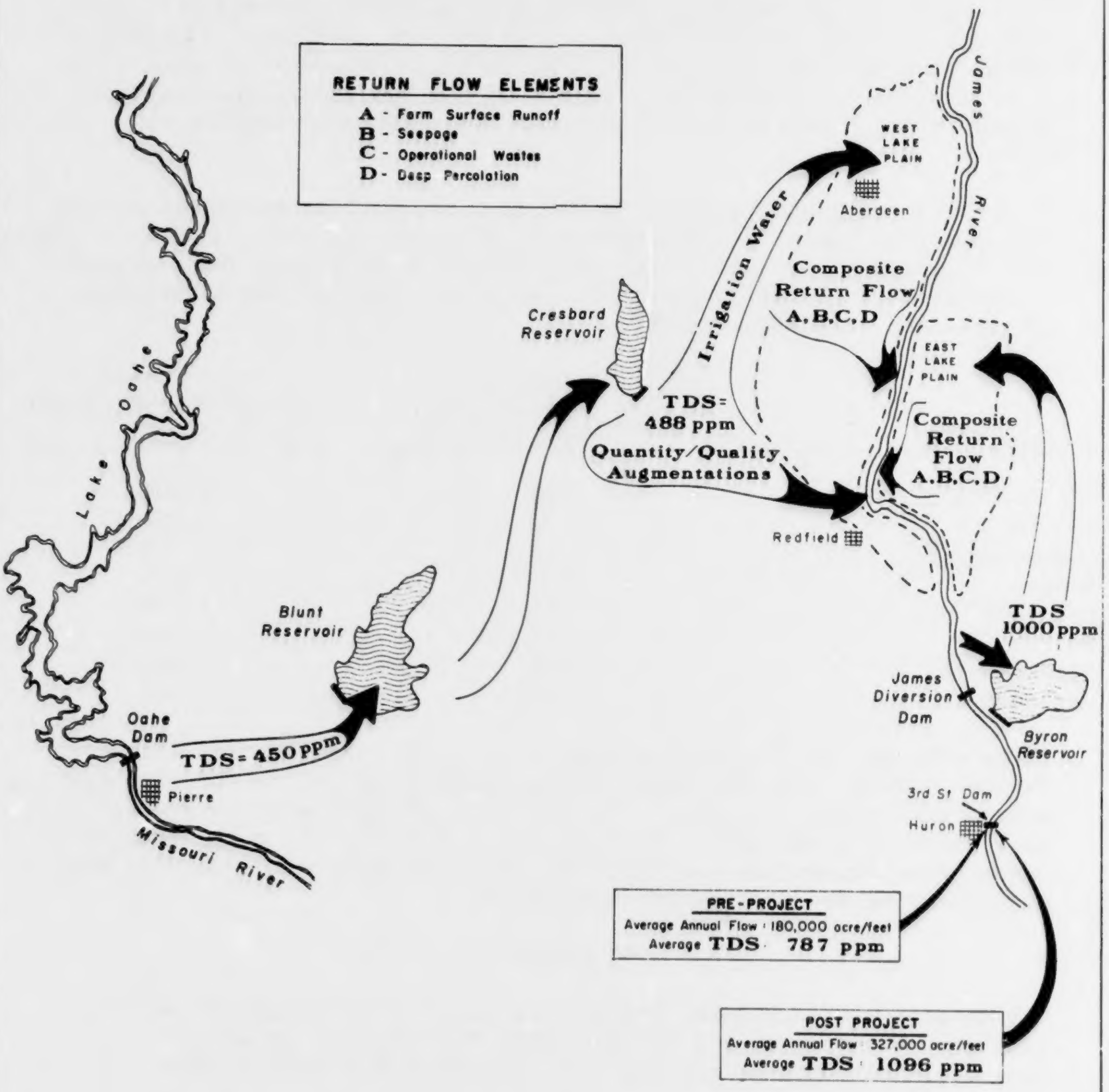

RETURN FLOW ELEMENTS
A - Farm Surface Runoff
B - Seepage
C - Operational Wastes
D - Deep Percolation
Lake Oahe
Oahe Dam
Pierre
Missouri River
TDS= 450 ppm
Blunt Reservoir
Cresbard Reservoir
TDS= 488 ppm
Quantity/Quality Augmentations
Irrigation Water
WEST LAKE PLAIN
Aberdeen
James River
Composite Return Flow A,B,C,D
EAST LAKE PLAIN
Composite Return Flow A,B,C,D
Redfield
TDS 1000 ppm
James Diversion Dam
Byron Reservoir
3rd St Dam
Huron
PRE-PROJECT
Average Annual Flow : 180,000 acre/feet
Average TDS 787 ppm
POST PROJECT
Average Annual Flow 327,000 acre/feet
Average TDS 1096 ppm

Figure 3

which will accrue to the James River. The analysis included complete development of 190,000 irrigable acres (77,000 has) and quality-quantity augmentation releases to the James River during the project operating season (April through October). The analysis did not include augmentation during the November-March period.

Results of the Oahe Unit return flow study indicate the following:

1. The TDS concentration of resultant James River streamflow at Huron can (and will) be maintained below 1,000 mg/1 (current South Dakota water quality standards) at all times during the operating season under project conditions. Quality augmentation will usually be required during the operation months of August, September and October. Sufficient capacity is available in the system to provide the necessary water for this dilution.

2. The TDS level of the James River during the nonoperating season (November through March) will exceed South Dakota water quality standards for TDS (1,000 mg/1) at times under Oahe Unit operations. At present the system is not designed for winter operation to make dilution water releases.

3. Sustained flows will be present in the James River during the winter months when natural flows have been characteristically quite low. This aspect will assure the City of Huron an ample quantity of raw water during extended periods of low natural streamflow. In addition, permanent flow conditions which will be present should greatly reduce taste and odor problems which occasionally occur in the winter months, and should enhance the river's capability to support wildlife and a continuing fish population.

4. The variation in TDS concentration in the river will reduce after the development of the Oahe Unit compared to what it is under natural conditions. This stabilization of the TDS level should reduce water treatment problems for Huron, possibly resulting in a cost savings.

5. A thorough review of impacts on James River water quality should be conducted by local, state, and federal specialists as project development progresses. Flexibility within the ongoing project design offers several alternatives relative to a winter water supply for the City of Huron, while satisfying the primary

purposes of the Oahe Unit - irrigation of 190,000 acres(77,000 has) in the Lake Plain area, municipal water supply for over 100,000 people, recreation development, and wildlife enhancement. Furthermore, project effects on the James River will occur gradually over a 16-year period and will be closely monitored.

BIBLIOGRAPHY

Dutt, G. R. and M. J. Shaffer. June 1972. A Composite Model for Predicting Nitrates and Other Solutes of Agricultural Drain Water. College of Agriculture, University of Arizona, Tucson, Arizona.

Shaffer, M. J. and R. W. Ribbens. October 1974. Generalized Description of Return Flow Quality Simulation Model. U.S. Department of the Interior, Bureau of Reclamation. Denver, Colorado.

U.S. Department of the Interior, Bureau of Reclamation. January 1976. Oahe Unit, Water Quality James River. Huron, South Dakota.

U.S. Department of the Interior, Bureau of Reclamation. September 1975. Draft Summary Report, Water Quality and Return Flow Study, Initial Stage Oahe Unit. Huron, South Dakota.

U.S. Department of the Interior, Bureau of Reclamation. December 1973. Final Environmental Statement, Oahe Unit, Billings, Montana.

U.S. Department of the Interior, Bureau of Reclamation. May 1965. Report on Oahe Unit, James Division-South Dakota, Missouri River Basin Project, Huron, South Dakota.

DETAILED RETURN FLOW SALINITY AND NUTRIENT SIMULATION MODEL

Marvin J. Shaffer[1]

INTRODUCTION

In recent years Federal and State agencies, environmental groups, congressional committees, the courts, and others have requested information on the projected quality and quantity of return flows from proposed and existing irrigation projects. Concentrations of total dissolved solids (TDS), the major cations and anions, nutrients, dissolved oxygen (DO), trace elements, pesticides, and other constituents have been included on the list of desired parameters. In response to this interest and general scientific interest in the subject, an open-ended return flow quality model has been evolving over the past 15 years. The model described in this paper represents the current status of the model as maintained by the U.S. Bureau of Reclamation. Changes and additions are constantly being made to the model to improve its reliability and widen its range of capabilities.

OVERALL MODEL

The model consists of several subprograms written in Fortran IV computer language which simulate unsaturated and saturated water flow, solute transport, and biological and chemical processes in the plant-soil-acquifer system. A generalized cross section of the modeled system is shown in figure 1. The simulation process begins at the soil surface and follows the chemical, physical, and biological processes through the unsaturated and saturated zones to tile drains.

Water flow is simulated in one dimension in the unsaturated zone and in two dimensions below the water table. Submodels are included for irrigation scheduling, transient unsaturated flow, chemical and biological reactions and solute transport in both the unsaturated and saturated zones, transient water table elevations and drain discharges, steady-state flow line positions and travel times (saturated zone), mixing of quality discharges from individual flow tubes, interfacing of other submodels, and computer graphics.

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The model generates transient predictions throughout the system for concentrations of Ca^{++}, Mg^{++}, Na^{+}, HCO_3^{-} , $CO_3^{=}$, Cl^{-}, $SO_4^{=}$, NO_3^{-}, NH_4^{+}, organic-N, and urea. Water flow results are generated in terms of parameters such as soil-water contents, water table positions, deep percolation volumes, drain discharges, travel times, and tube volumes.

The reaction portions of the model consist of subprograms based on chemical equilibrium and chemical kinetic theories. Both approaches are utilized depending on the constituent and the process being simulated.

MODEL HISTORY

A better appreciation of the model can be obtained from a brief review of its historical development. Over the years a number of researchers have made direct or indirect contributions to the model. Dutt, et al., in several early papers (Dutt, 1962, 1964; Dutt and Doneen, 1963) established the basic concepts contained in the chemical equilibrium submodels. Later a finite difference solution to the unsaturated flow equation (Hanks and Bowers, 1962; Warrick, Nielson, and Biggar, 1971) was combined with the chemical equilibrium subprograms and the kinetic nitrogen transformation submodel of Shaffer, et al. (Shaffer, Dutt, and Moore, 1969). The resulting model (Dutt, Shaffer and Moore, 1972) integrated solute transport and reactive processes in the saturated zone. The simulation was one dimensional from the soil surface to a fixed water table.

This model was later extended by adding the saturated flow submodels of Ribbens (1970, 1972) which simulated two dimensional flow from the water table to tile drains. The chemical equilibrium submodels were adapted to operate in the region (Dutt and Shaffer, 1972). Still later the Bureau's irrigation scheduling model was included to schedule irrigation inputs and supply consumptive use estimated to the unsaturated flow submodel, as well as provide a shortcut method of estimating deep percolation volumes. The nitrification equations were modified to include a transition state approach (Shaffer and Dutt, 1973) and a crude denitrification submodel (Shaffer, Ribbens, and Huntley, in press) was added to account for the process in the saturated zone.

A number of user oriented features have been added to the model to

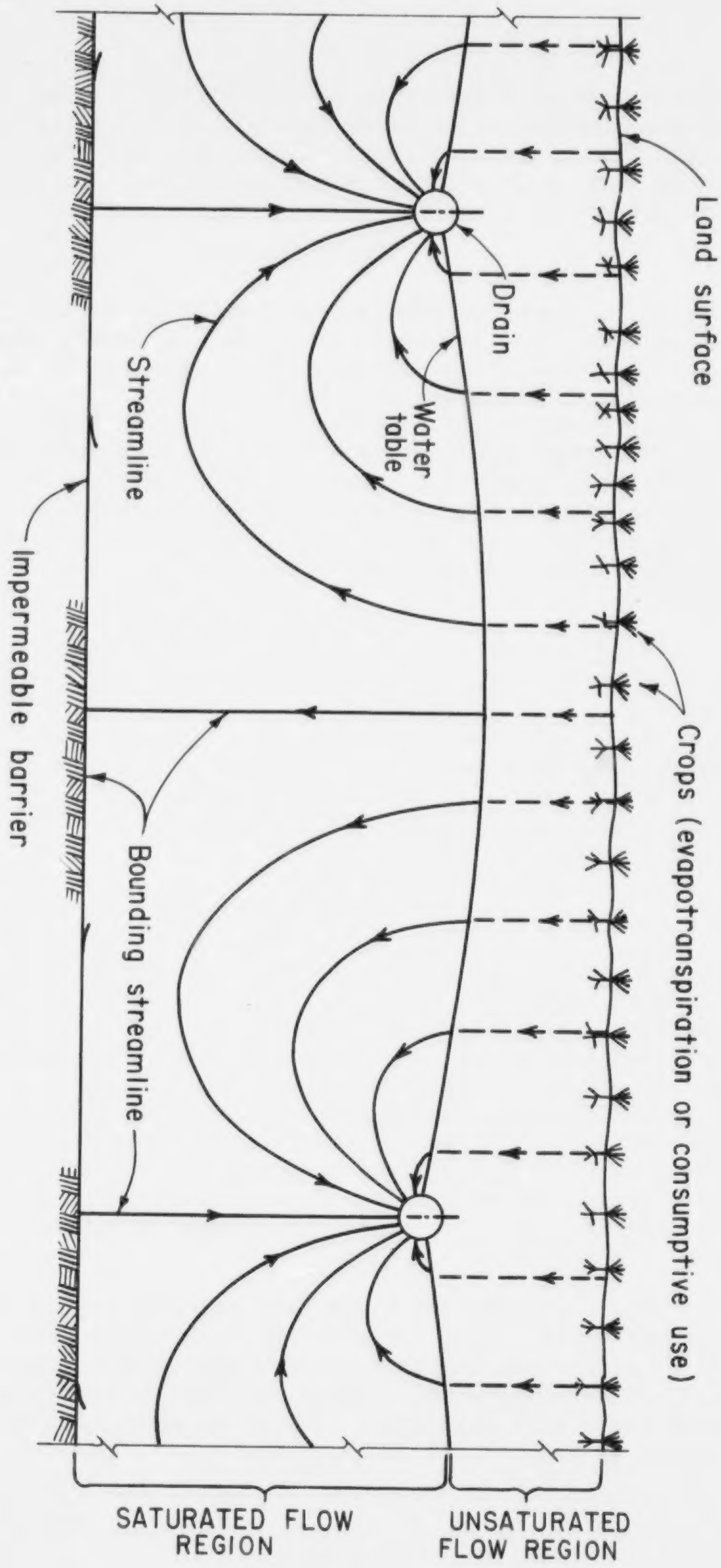
Land surface
Crops (evapotranspiration or consumptive use)
Drain
Water table
Streamline
Impermeable barrier
Bounding streamline
SATURATED FLOW REGION
UNSATURATED FLOW REGION

FIG. I TYPICAL VERTICAL SECTION THROUGH DRAINAGE FIELD

provide greater flexibility and easier use. These include bypass options, options which allow multiple applications of certain submodels, microfilm or microfiche plotting, and a detailed user's manual with program listings and sample problems (Shaffer, Ribbens, and Huntley, in press).

BASIC CONCEPTS

Like all attempts to simulate real-world phenomena, the model was developed from a set of basic hypotheses or assumptions. It was assumed that the plant-soil-aquatic system can be dissected into subsystems for analysis and these subsystems recombined in the model to yield predictions about the entire system. Each subsystem was modeled independently using a set of deterministic equations to simulate the appropriate physical, chemical, and biological processes. Conservation of mass was assumed in each subsystem and in the overall combined model. The rates of change in mass for each constituent as a result of each process were integrated numerically throughout the system.

The amount of detail contained in the model represents a compromise between the extreme detail theorists would like to include in a return flow simulation model and the extreme simplicity some practitioners insist on. Figure 2 illustrates the middle ground between these two views. The most successful models usually are those with just enough detail to adequately accomplish the objectives of the study. The peak of the solid curve probably represents the best model for a given application.

MODEL SUBSYSTEMS

A schematic representation of the major submodels within the overall model appears in figure 3. The irrigation scheduling submodel calculates irrigation application dates and depths and crop evapotranspiration for use by the unsaturated flow submodel, and also may be used to estimate deep percolation volumes for use in the drainout submodel. The Jensen-Haise method (Jensen, Robb, and Franzoy, 1970) is utilized to compute evapotranspiration rates. Eventually, the unsaturated flow submodel will be upgraded to use the Jensen-Haise method for evapotranspiration and schedule its own irrigations. At this point, the scheduling submodel will no longer be needed for these purposes.

Soil-water contents and fluxes are computed by the unsaturated flow submodel based on nodes within the unsaturated zone. An implicit finite difference solution to the unsaturated flow equation is utilized to compute the desired information for flow to/from a fixed water table with extraction of soil-water by crop roots. The root pattern is taken as fixed over time.

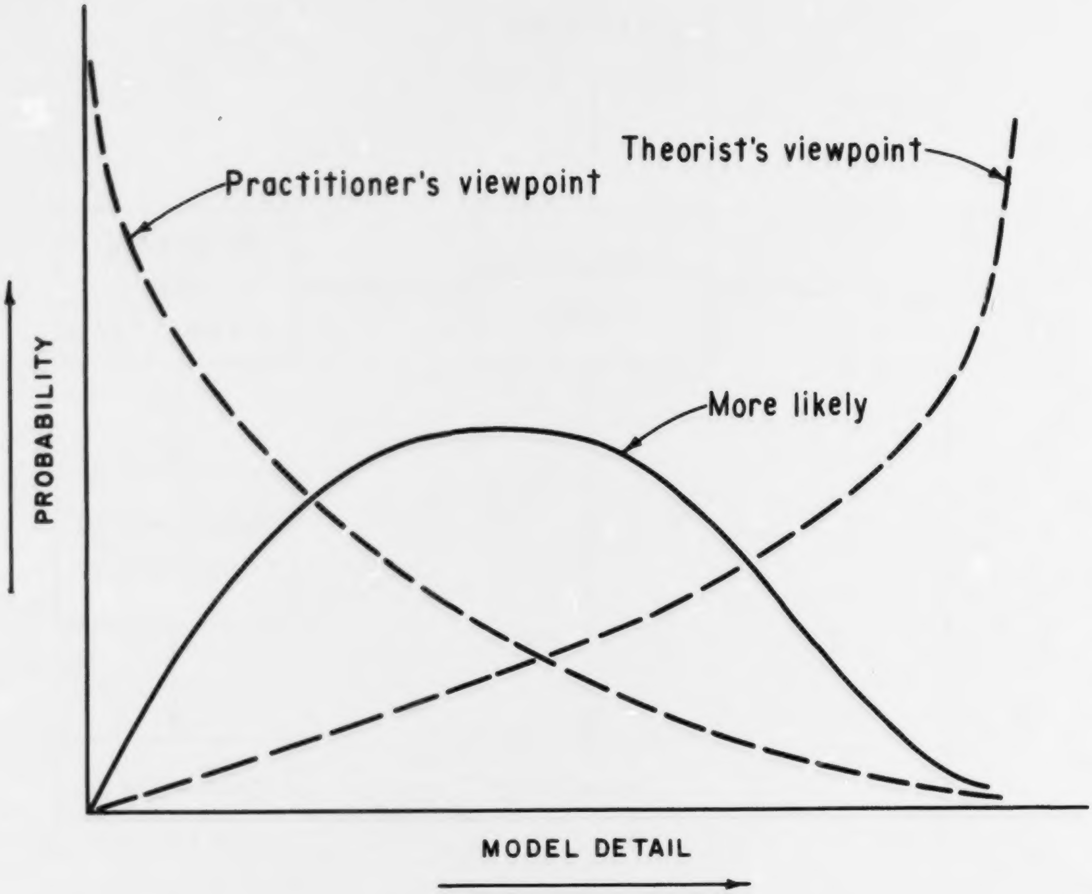

Fig. 2 Probability of having the best model for a given application.

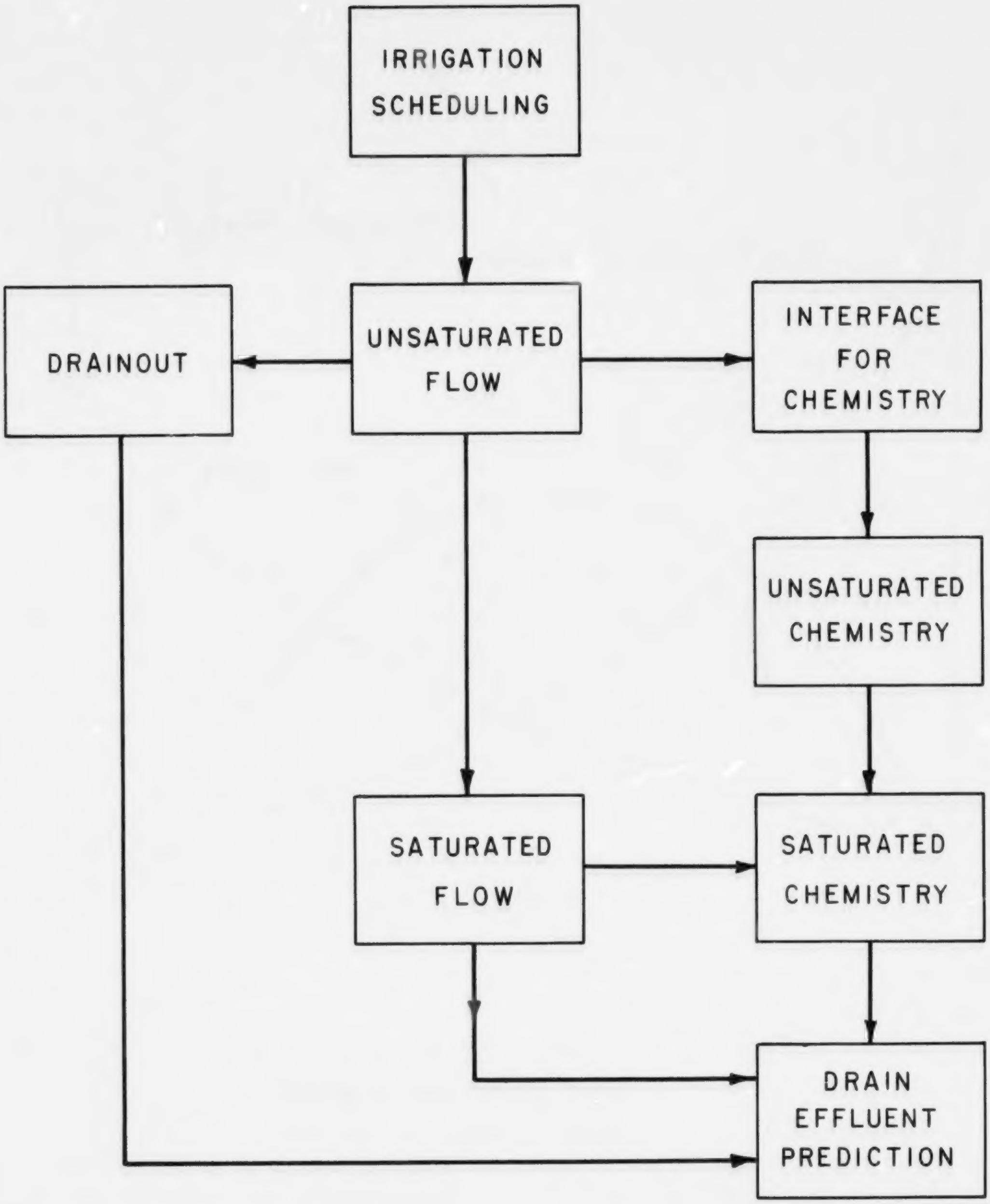
IRRIGATION SCHEDULING
DRAINOUT
UNSATURATED FLOW
INTERFACE FOR CHEMISTRY
UNSATURATED CHEMISTRY
SATURATED FLOW
SATURATED CHEMISTRY
DRAIN EFFLUENT PREDICTION

FIG. 3 SCHEMATIC REPRESENTATION OF WATER QUALITY MODEL

The interface submodel converts soil-water contents and fluxes on a nodal basis to mean water contents for finite soil volumes (segments) and fluxes at the top and bottom boundaries of these segments. The segment concept is utilized by the unsaturated chemistry submodel which is a plate-type model with complete mixing and reactive chemistry associated with each segment over each time step.

Unsaturated chemistry uses both chemical equilibrium and chemical kinetic subprograms. The chemical equilibrium subprogram simulates the dissolution and precipitation of calcium carbonate (lime) and calcium sulfate (gypsum), ion pair reactions for $CaSO_4^\circ$ and $MgSO_4^\circ$, Ca-Na, Ca-Mg, and Na-NH_4 ion exchange, and Ca-HCO_3-CO_2 interactions. Activity coefficients are computed using Debye-Huckel theory.

The chemical kinetic submodel computes reaction rates for nitrogen transformations including nitrification, immobilization, mineralization, and urea hydrolysis. The rate equations are statistical, transition state, or zero order depending on the particular nitrogen transformation or model option being considered.

The unsaturated chemistry submodel uses the soil-water content and flux data generated by the unsaturated flow submodel (via the interface submodel) to compute solute movement and redistribution within the unsaturated zone. Soluble chemical species are assumed to move with the water from one segment to the next. A complete mix is assumed at each step in time and space. No direct method is included to simulate solute movement due to mechanical dispersion and molecular diffusion. These processes are indirectly modeled in the simulation procedure by numerical dispersion. Use of at least 10 segments and restrictions on the maximum water flux rate appear to adequately account for dispersion and diffusion (Wierenga et al., 1974.). Additions of a correction term for numerical dispersion and another term for dispersion and diffusion could be made at the expense of increased computer execution times.

Crop uptake of NO_3^- and NH_4^+ is simulated by a subprogram of unsaturated chemistry. Two simulation methods are available to the user. The first involves the uptake of nitrogen at a rate which is directly proportional to the consumptive use. The second involves the use of uptake rates for nitrogen as supplied in the input data. In both methods the user supplies the fractions of total uptake as NH_4^+ AND NO_3^-.

The drainout submodel computes the transient response of the drains to deep percolation from the root zone. The Bureau's drainage equations used for design of drain spacings occur in this submodel.

The saturated flow submodel is a steady-state program designed to calculate the average position of stream paths or lines to the drain (Kirkham, 1958). A two-dimensional flow system is utilized and average flow tube volumes and travel times are calculated for use by the saturated chemistry and drain effluent prediction submodels, respectively.

The saturated chemistry submodel utilizes the chemical equilibrium subprograms of the unsaturated chemistry submodel. Each flow tube in the saturated region is subdivided into a number of segments of equal volume. Water and dissolved constituents from deep percolation are accumulated until the pore volume of one segment is moved towards the drain by piston displacement. Chemical transformations are computed after each displacement by calling the chemical equilibrium subprograms. Denitrification is simulated as deep percolation water crosses into the saturated zone.

The drain effluent prediction submodel mixes the water from each drainage tube in the saturated zone. Mean travel times, monthly drainage discharges, and water qualities generated in previous submodels are used to calculate transient qualities for the soluble constituents at the drain.

MODEL VERIFICATION

The model subprograms have been verified independently using laboratory soil columns, lysimeters, and small field plots (Dumm, 1968; Dutt, Shaffer, and Moore, 1972; Dutt and Tanji, 1962; Dutt, Terkeltoub, and Rauschltolb, 1972; Shaffer and Dutt, 1973; Wierenga, et al., 1974). Figures 4 and 5, taken from Weirenga et al. (1974) illustrate the type of agreement between observation and prediction obtained in the unsaturated zone. Figure 4 shows profiles for Cl^- obtained after leaching the column with 18 and 21 meq/l Cl^-. The agreement obtained here was based on the numerical dispersion obtained from 10 soil segments and flux rates always less than the current water content of the soil segment. It appears that the model adequately accounted for dispersion and diffusion in this example.

In the same study, good agreement also was obtained for $SO_4^=$, but Mg^{++} and HCO_3^- profiles were somewhat in error indicating a need for further model refinements.

Figures 6 and 7 contain observed and predicted results from a field application of the model made in southwestern Colorado. The approximate physical and chemical processes associated with 890 hectares of irrigated land were simulated over a period of 75 years. This particular simulation represents only a partial verification of the

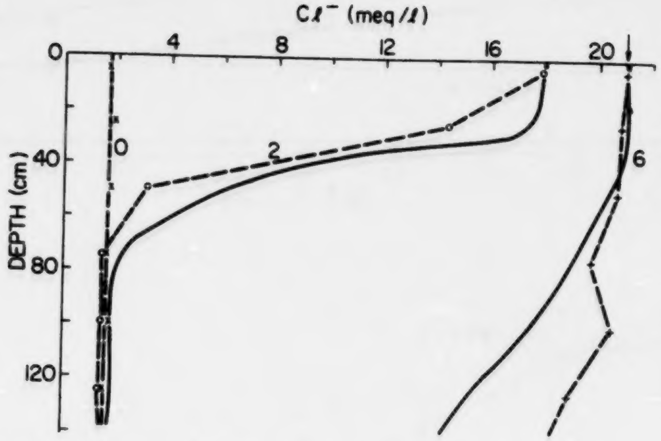

Fig. 4 Observed (*dashed lines*) and predicted (*solid lines*) chloride distributions after 2 and 6 irrigations with water containing 18 meq/liter chloride during the first two irrigations, and 21 meq/liter during the latter irrigations.

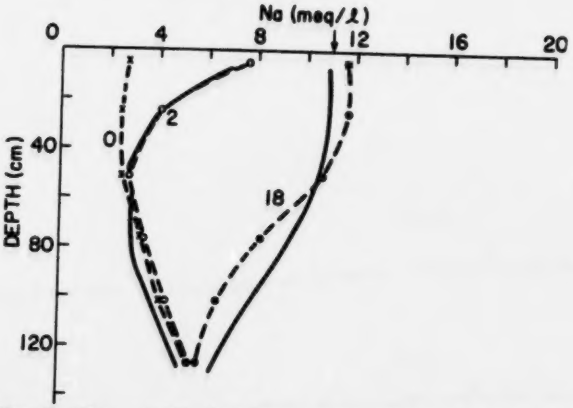

Fig. 5 Observed (*dashed lines*) and predicted (*solid lines*) sodium distributions after 2 and 18 irrigations with water containing 11 meq/liter sodium.

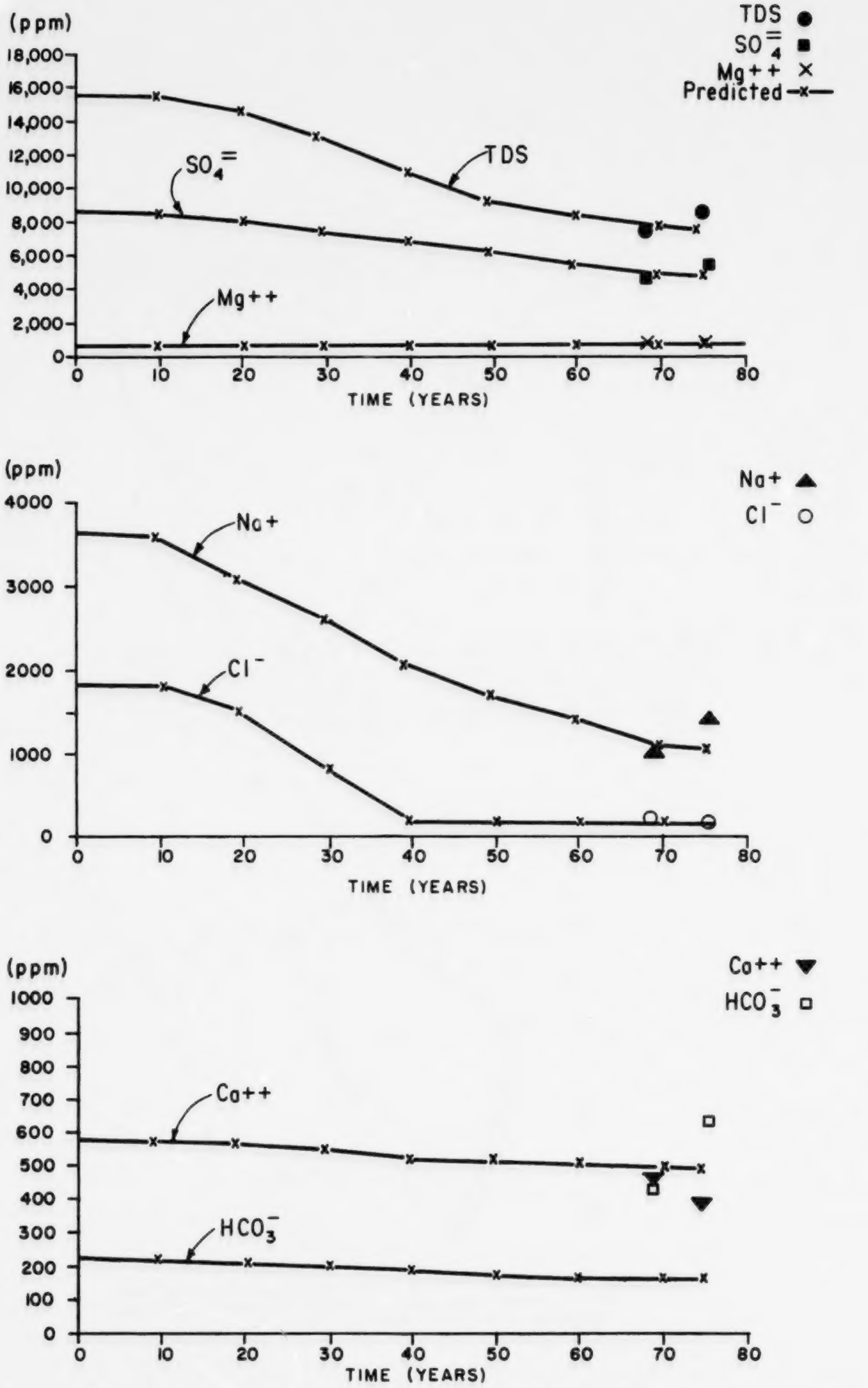

FIG. 6 PREDICTED AND OBSERVED WATER QUALITY NAVAJO WASH (CHEMISTRY INCLUDED)

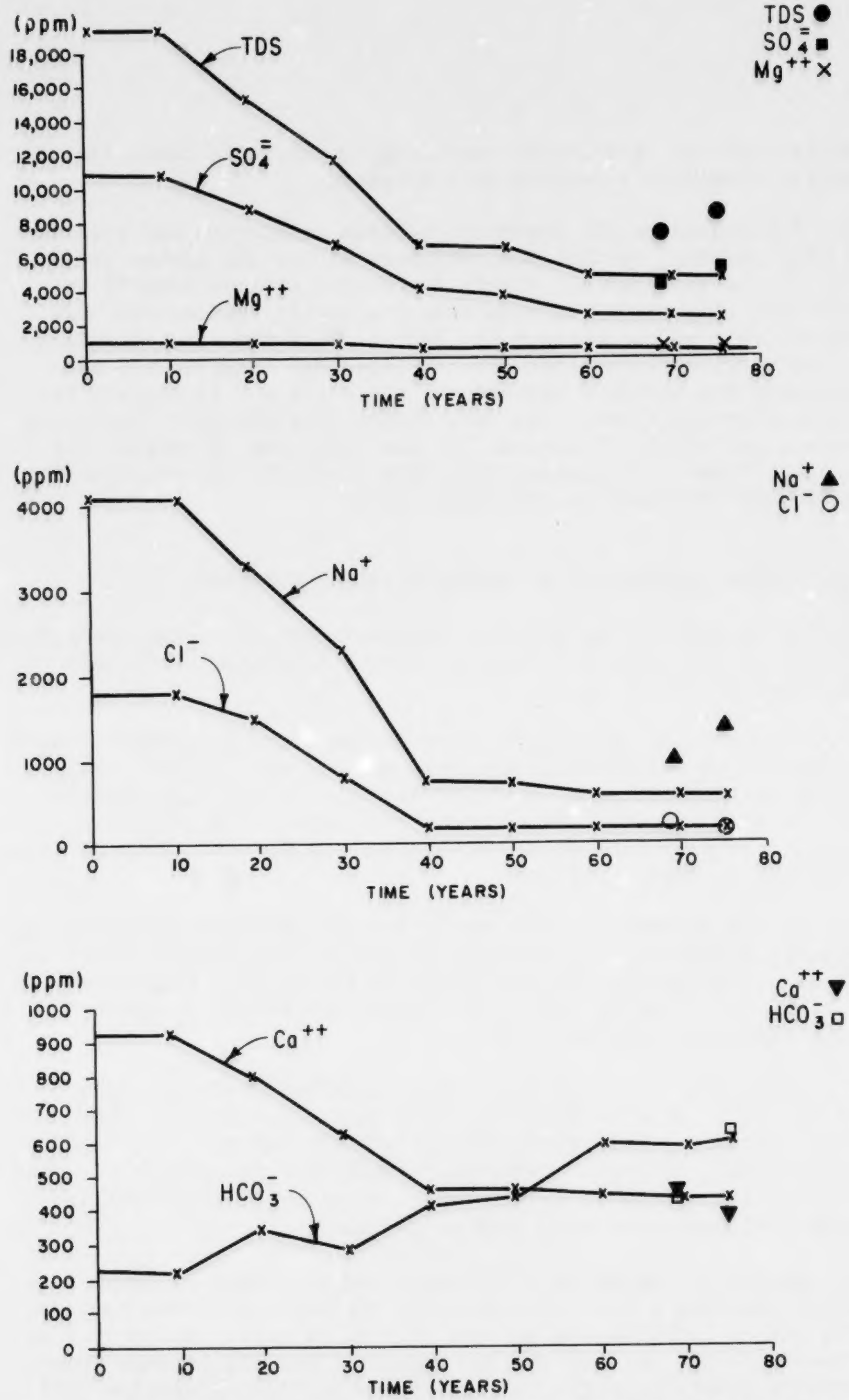

FIG. 7 PREDICTED AND OBSERVED WATER QUALITY NAVAJO WASH (CHEMISTRY OMITTED)

model because the irrigation scheduling, unsaturated flow, and unsaturated chemistry submodels were bypassed.

Figure 6 illustrates the agreement between prediction and observation when chemical equilibrium processes within the system are included in the simulation. Figure 7 contains similar results but without the chemistry. In this case the quality parameters were conservatively routed through the system. For the case including the chemistry, agreement between predicted and observed TDS concentrations was within 8 percent for the soils and 12 percent for irrigation return flows. The case without the chemistry indicated agreement was within 35 percent for the soils and 28 percent for the return flows. It appears from this analysis that the chemistry is extremely important in this study area.

MODEL APPLICATION TO LARGE IRRIGATED ACREAGES

The model is designed to simulate chemical, physical, and biological processes in the plant-soil-aquifer system described previously and illustrated in figure 1.

Application to large irrigated areas involves the selection of data sets (called master sites in the case of soil and aquifer data) which adequately represent field conditions. These data are then used to make a number of independent runs with the model. The assumption is made that field variability can be adequately defined and modeled by this procedure.

Recent data indicate that relatively few master sites are needed to adequately represent soil salinity in return flow studies where predictions of long-term average or median return flow salinities are the objective. Studies with other objectives would be expected to require different amounts of data.

In the past, selections of model input data were made by field personnel with the most knowledge of a particular project area. Current and future selections are and will be based to some degree on professional judgment. However, statistical, mapping, and other techniques are slowly being developed to improve the reliability of data collection and reduction procedures.

As an example of the kinds of difficulties presented by field data, figure 8 contains a plot of cumulative probability versus soil salinity ($EC_e \times 10^3$) for the surface 30.5 cm of soil. Other 30.5 cm increments to 152 cm show similar trends. Some 925 borings from the Middle Souris area (25,980 ha) of the Garrison Diversion Unit, North Dakota, are represented in the figure. Soil salinity shows

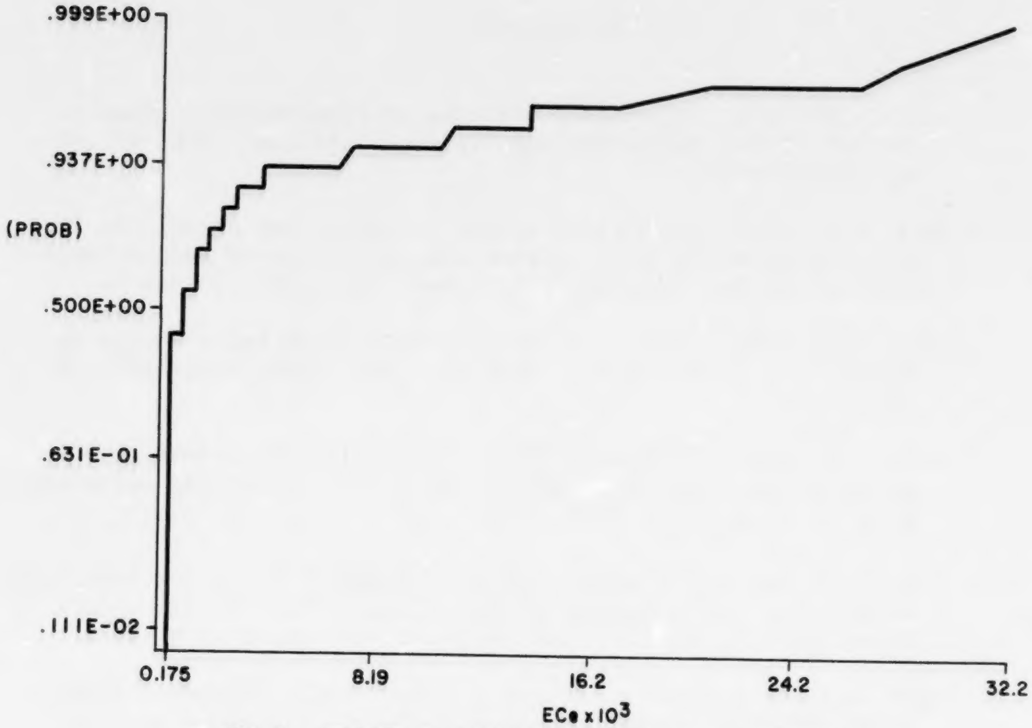

FIG. 8 FRACTILE DIAGRAM - DEPTH 0-12 INCHES

a strong positive skewing with many low salinity soils and a few pockets of high salinity. The arithmetic mean, geometric mean, median, mode, and mean 2/ for the $EC_e \times 10^3$ values are 1.61, 0.67, 0.64, 0.16, and 1.30 mmhos, respectively. Depending on which estimator of central tendancy is used and which method is used to calculate the value for the estimator, a range of conclusions can be made concerning soil salinity.

SUMMARY

An irrigation return flow quality and quantity model has been developed over the past 15 years. The model is evolving constantly but currently simulates water flow, solute transport, and chemical and biological reactions in the unsaturated and saturated zones. Water quality constituents modeled include TDS, Ca^{++}, Na^{+}, Mg^{++}, NH_4^{+}, HCO_3^{-}, $CO_3^{=}$, Cl^{-}, $SO_4^{=}$, NO_3^{-}, organic-N, and urea. The model has been verified using laboratory columns, lysimeters, small field plots, and large irrigated areas. Future plans include the addition of phosphates, pesticides, and trace elements to the constituent list handled by the model.

2/ Based on the assumption of a log-normal distribution.

REFERENCES

Dumm, L.D. 1968. Subsurface drainage by transient-flow theory. Journal of the Irrigation and Drainage Division. ASCE Vol. 94, No. IR4:505-519.

Dutt, G.R. 1962. Prediction of the concentration of solutes in soil solutions for soil systems containing gypsum and exchangeable Ca and Mg. Soil Sci. Soc. Amer. Proc. Vol. 26:341-343.

Dutt, G.R. 1964. Effect of small amounts of gypsum in soils on the solutes of effluents. Soil Sci. Soc. Amer. Proc. Vol. 28: 754-757.

Dutt, G.R. and L.D. Doneen. 1963. Predicting the solute composition of the saturation extract from soil undergoing salinization. Soil Sci. Soc. Amer. Proc. 27:627-630.

Dutt, G.R. and M.J. Shaffer. 1972. A Computer Model for Predicting Nitrate and Other Solutes of Agricultural Drain Water. Final Report to U.S. Bureau of Reclamation, University of Arizona.

Dutt, G.R., M.J. Shaffer, and W.J. Moore. 1972. Computer Simulation Model of Dynamic Bio-Physiochemical Processes in Soil. Technical Bulletin 196, Agricultural Experiment Station, University of Arizona, Tucson.

Dutt, G.R. and K.K. Tanji. 1962. Predicting concentrations of solutes in water percolated through a column of soil. J. Geophys. Res. 69:3437-3493.

Dutt, G.R., R.W. Terkeltoub, and R.S. Rauschltolb. 1972. Prediction of gypsum and leaching requirements for sodium-affected soils. Soil Science 114:93-103.

Hanks, R.J. and S.A. Bowers. 1962. Numerical solution of the moisture flow equation for infiltration into layerd soils. Soil Sci. Soc. Amer. Proc. Vol. 26:530-534.

Jensen, M.E., D.C.N. Robb, and C.E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. Journal of the Irrigation and Drainage Division. ASCE Vol. 96., No. IR1:25-28.

Kirkham, D. 1958. Seepage of steady rainfall through soil into drains. Transactions, American Geophysical Union. 39:892-908.

Ribbens, R.W. 1970. Report on Water Quality Model Developed in Connection with Interagency Wastewater Studies. San Luis Drain, California. U.S. Department of the Interior. Bureau of Reclamation. Engineering and Research Center, Denver, Colorado.

Ribbens, R.W. 1972. Report on Water Quality and Return Flow Study for Souris Loup Area of the Initial Stage of the Garrison Diversion Unit. Appendix B. Results of Water Quality Return Flow Model. U.S. Department of the Interior. Bureau of Reclamation: 33 pages.

Shaffer, M.J. and G.R. Dutt. 1973. Nitrification in soil-water systems: A computerized activated complex model. Proceedings of the First World Congress on Water Resources. Chicago, Illinois. 4:284-294.

Shaffer, M.J., G.R. Dutt, and W.J. Moore. 1969. Predicting Changes in Nitrogenous Compounds in Soil-Water Systems. Collected Papers Regarding Nitrates in Agricultural Waste Water. U.S. Government Printing Office. Washington, D.C.:15-28.

Shaffer, M.J., R.W. Ribbens, and C.W. Huntley. In press. Prediction of Mineral Quality of Irrigation Return Flow. Volune V. Detailed Return Flow Salinity and Nutrient Simulation Model. U.S. Environmental Protection Agency. Ada, Oklahoma: 400 pages.

Warrick, A.W., D.R. Nielson, and J.W. Biggar. 1971. Simultaneous water and solute transfer for an unsaturated soil. Water Resources Research. Vol. 7:1216-1225.

Wierenga, P.J., M.J. Shaffer, S.P. Gomez, and G.A. O'Connor. 1975. Predicting ionic distributions in large soil columns. Soil Sci. Soc. Amer. Proc. 39:1080-1084.

TRANSPLANTATION OF JUNCUS SPP. ON SALINE SOILS IN EGYPT

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Amal A. Abdel Wahid and M. A. El-Demerdash 1/

INTRODUCTION

The saline lands of Egypt are associated with the littoral salt marshes of the Mediterranean Sea (northern coast) and of the Red Sea (eastern coast), with the inland salt marshes of the oases and depressions of the Western Desert, as well as with the salt marshes of the northern lakes of the Nile Delta, viz: El-Manzala, El-Borollus, Edku, and Mariut (Fig. 1). These vast areas are formed of sand and/or sand mixed with silt. They can be easily irrigated with sea water (in the case of the coastal lands), with the artesian water (brackish) of the wells and springs of the oases and depressions, and with the brackish water of the northern lakes. The interest of the present work is to cultivate certain areas of these saline lands with salt tolerant plants that proved to be of economic importance, i.e., non-conventional crops that may provide local raw materials for industries. Apart from that, the cultivation of the saline lands with halophytic plants is a biological way for soil desalination.

Juncus rigidus and *Juncus acutus* (salt tolerant fiber plants) were selected to be the first group of plants on which transplantation on saline soils would be experimented.

ECOLOGICAL CHARACTERISTICS

J. rigidus and *J. acutus* are closely related halophytes having the same vernacular name "Samar Murr" and belonging to the family Juncaceae. Both species are of the cumulative halophytes (Walter, 1961) lacking the regulating mechanisms of the succulents and excretive halophytes. They accumulate excess salts in the upper parts of their green culms, an advantage that characterizes *Juncus* spp. and may lead to desalination of saline soils. Referring to salt accumulating crop plants Boyko (1966) said: "Each harvest is ... diminishing the salt content in soil and/or groundwater ...".

J. rigidus is a densely tufted rush with slender pungent nodeless culms more than one meter high. It has sympodial creeping rhizomes developing leafy shoots (culms) every year. These rhizomes extend horizontally, exploiting wide areas, and produce vegetation within a few years (photos 1 and 2). In Egypt, *J. rigidus* is a common rush that flourishes in the saline and alkaline soils (photo 3) with total soluble salts up to 3-3.8% in the rhizosphere layer, which is mostly (> 80%) chlorides and partly (< 20%) sulfates.

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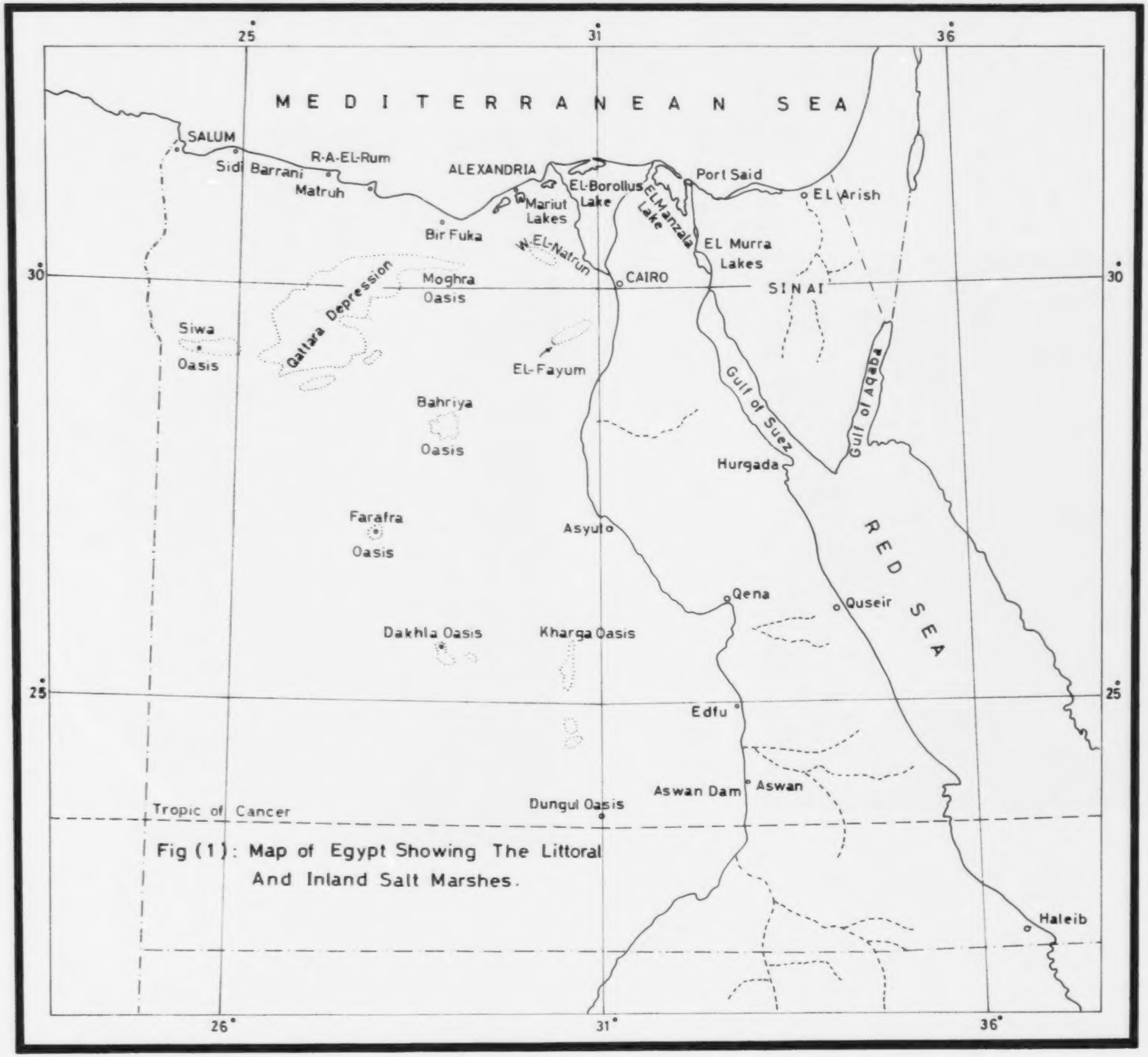
25
31
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MEDITERRANEAN SEA
SALUM
Sidi Barrani
R-A-EL-Rum
Matruh
ALEXANDRIA
Mariut Lakes
El-Borollus Lake
EL Manzala Lake
Port Said
EL Arish
Bir Fuka
W-EL-Natrun
EL Murra Lakes
CAIRO
SINAI
Moghra Oasis
Qattara Depression
Siwa Oasis
EL-Fayum
Bahriya Oasis
Gulf of Suez
Gulf of Aqaba
Hurgada
Farafra Oasis
Asyut
RED SEA
Qena
Quseir
Dakhla Oasis
Kharga Oasis
Edfu
Aswan Dam
Aswan
Dungul Oasis
Tropic of Cancer
Haleib

Fig (1): Map of Egypt Showing The Littoral And Inland Salt Marshes.

Photo 1: Juncus rigidus population, Wadi El-Natrun, Egypt. Notice the horizontal growth of the rhizomes and the culms.

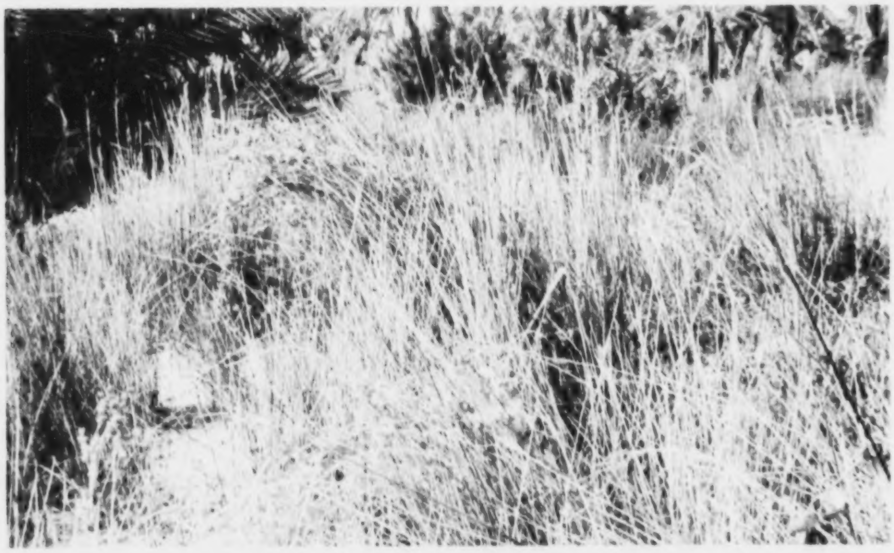

Photo 2: Dense growth of Juncus rigidus community of Siwa Oasis, Egypt.

Photo 3: Alkaline soil with surface salt crusts and exposed underground water where Juncus rigidus predominates in the salt marshes of Moghra Oasis, Egypt.

The biogeography of J. rigidus in Egypt shows that the plant is not only salt tolerant but it also tolerates a wide range of climatic changes. Its natural population is recorded in the semi-arid region of Egypt (salt marshes of the Mediterranean coast and those associated with the northern lakes of the Nile Delta) where the climate is mild (Tab. 1) and in the arid and extremely arid regions represented by the littoral salt marshes of the Red Sea and the inland salt marshes, where the climate is hot and dry.

J. rigidus community of Egypt is often formed of pure stands with extensive cover (up to 100%, photo 2). In certain instances the dominant plant is associated with a few halophytes, e.g., Halocnemum strobilaceum, Arthrocnemum glaucum, Salicornia fruticosa, Juncus rigidus, Cressa cretica, Limonium pruirosum, Inula crithmoides, etc.

J. acutus, on the other hand, has the same morphological aspects of J. rigidus; but the rhizomes of J. acutus grow in a special way giving rise to a great number of green culms that form circular tussocks of variable sizes (Photos 4 and 5). The community type dominated by J. acutus is widespread in the salt marshes of the semi-arid and arid regions (Mediterranean coast, Wadi El-Natrun and El-Fayium salt marshes), but it is either rarely recorded or absent from the salt marshes of the extremely arid region of Egypt (Migahid et al., 1955; Kassas and Zahran, 1967; Zahran and Girgis, 1970; and Zahran, 1976). The habitat of J. acutus is usually of the highly moistened soil in the downstream zone of the sedge meadow close to the reed swamps. The total soluble salts of the

Table 1: Meteorological particulars of three stations representing the semi-arid (Burg El-Arab), arid (El-Fayium) and extreme-arid (El-Kharga Oasis) climatic belts of Egypt.

Month	Semi-Arid (Burg El-Arab)				Arid (Al-Fayium)				Extreme-Arid (El-Kharga Oasis)			
	R	T	RH	E	R	T	RH	E	R	T	RH	E
Jan	49.0	13.1	72	4.8	2.0	11.4	74	3.01	0.0	12.7	48	5.21
Feb	31.0	14.6	74	4.8	2.0	12.5	64	4.46	0.0	14.1	42	6.40
Mar	12.4	16.4	72	5.4	1.0	16.1	60	6.08	0.0	18.4	38	9.03
Apr	3.1	19.6	66	6.5	1.0	20.3	49	8.71	0.0	23.8	34	11.57
May	3.1	22.5	67	6.9	0.0	25.0	43	11.62	0.0	27.9	31	13.96
Jun	0.0	24.6	68	6.3	0.0	27.5	46	13.42	0.0	30.9	28	15.32
Jul	0.0	26.4	74	7.0	0.0	28.1	51	11.97	0.0	30.8	28	15.13
Aug	0.0	26.2	76	6.6	0.0	27.9	57	10.24	0.0	30.6	30	14.40
Sep	0.5	25.2	68	7.8	0.0	25.8	63	7.70	0.0	28.4	36	13.05
Oct	9.2	22.9	70	6.8	0.0	22.7	66	6.40	0.0	24.9	38	10.35
Nov	28.8	19.8	71	6.6	1.0	18.7	72	4.48	0.0	19.4	44	7.34
Dec	56.5	15.6	77	5.4	5.0	13.6	74	3.13	0.0	14.1	49	5.14
Total	192.9	-	-	-	12.0	-	-	-	0.0	-	-	-
Mean Annual	-	20.1	70	6.3	-	20.8	60	7.59	-	23.0	37	10.57

Taken from the Climatological Normals of Egypt (1951).

R = Rainfall (mm)
T = Air temperature (°C)
RH = Relative humidity (%)
E = Evaporation (mm/day)

rhizosphere layers ranges between 1.2-1.7%, which is mostly chlorides. The associate species of the *J. acutus* community include moisture loving plants, e.g., *Berula erecta*, *Samolus valerandi*, etc., and salt marsh plants, e.g., *Cyperus laevigatus*, *J. rigidus*, *Aeluropus brevifolius*, etc.

ECONOMIC IMPORTANCES

Juncus plants have many economic uses. Their seeds were employed in oriental medicine as antidiarrhetics and as diuretics (Täckholm and Drar,

Photo 4: A community type dominated by Juncus acutus, Mediterranean Salt Marshes, Egypt. Notice the circular tussocks of J. acutus culms.

Photo 5: Close-up view of Juncus acutus tussock. Notice the clusters of fruit.

1954) and can be used for the production of glycerides and phospholipids (Osman et al., 1975). The green culms of Juncus are used also as raw material in the fiber industry, especially in making paper. "This wild rush could be developed as raw material for printing paper of high quality" (Boyko, 1966). This was confirmed by studies on fiber lengths and on chemical characteristics of Juncus culms carried out by Zahran et al. (1972). Juncus culms produced paper pulps with strength properties much higher (grade index of 73%) than those of other local raw materials (rice straw, grade index = 24%, and bagasse, grade index = 42%). compared to the pulp obtained from the soft wood kraft (grade index = 100%). However. rice straw and bagasse pulps need to be mixed with kraft pulp to produce paper, while Juncus pulp could be used along.

Consequently, in Egypt, if sufficient amount of Juncus culms are available to paper mills, the size of paper pulp imports may be changed. However, large scale economic production of paper entails large production of Juncus plants from homogeneous plant growth. This is not available from the heterogeneous natural population of Juncus spp. in Egypt. Hence, it will be important to study the main factors affecting the productivity of such plants under agricultural practices. The effect of these factors on fiber qualities is of equal importance.

The basic idea is to take advantage of the halophytic nature of Juncus and to cultivate it in areas of low productivity due to salinity. This will provide raw materials for paper industries through management and use in areas that are otherwise not economically productive.

TRANSPLANTATION EXPERIMENTS

J. rigidus and J. acutus can be planted either from seeds (Zahran, 1975) or rhizomes (El-Bagouri et al., 1976). The latter way is preferable as rhizomes produce new culms in a short time.

The experimental area is a part of the badly drained saline soil associated with Manzala lake. The depth of the underground water table (brackish: EC = 12,327 mmhos/cm, Cl = 5,041 ppm, and SO_4 = 1,204 ppm) is shallow (at about 10-15 cm in summer and at about 50-70 cm in winter below soil surface). The soil is usually saturated with water, a factor that decreases its aeration, and consequently, reduces its productivity. Analysis of representative soil samples collected from the experimental site showed that the soil had the following physical and chemical characteristics: clayey in texture, black in color, alkaline in reaction (pH = 8.5-8.8), organic matter content = 1.14-1.2%, calcium carbonate content = 4.26 - 4.32%, EC = 980-1,470 mmhos/cm, and CEC = 37 meq/100 gm soil.

EXPERIMENT I: GROWTH

Materials and Method

An area of 3,528 m^2 of the above described land was prepared and divided into 84 plots (6 x 7 m each) for the Juncus transplantation experiment (42 plots for J. rigidus and 42 plots for J. acutus). Rhizomes of Juncus spp. were collected from Juncus natural growth in Mariut salt marshes and were carried (on September 30, 1974) to the locality of the experiment at Manzala. Except for rainfall, which is about three times higher in Mariut (mean annual of 192 mm) than in Manzala (mean annual of 66.3 mm), climatic conditions of Mariut and Manzala are almost comparable (mean maximum temperature of 24.9° C and 24.6° C; mean minimum temperature of 15.9° C and 16.5° C; mean relative humidity of 70% and 72%; mean evaporation of 5.2 mm/day and 6.7 mm/day, respectively). In both areas rainfall is usually confined to the winter (Climatological Normals of Egypt, 1941-1960).

On the first of October, 1974, the experiment was started by transplanting 12, more or less equal sized, pieces of J. rigidus and J. acutus at equal distances and at about 5-10 cm depth, in each plot. Irrigation using Nile water was carried out every 5 days in summer, but during winter (wet season) irrigation intervals were extended to 7 days. The irrigation water at the Manzala area, being near Lake Manzala and being taken from the most downstream part of the River Nile, contained relatively high proportions of soluble matter (EC of 529 mmhos/cm, Cl of 71 ppm and SO_4 of 44 ppm). The experiment continued for one year, and harvesting (cutting aerial green culms) was carried out on October 1, 1975. The following measurements were taken: a) number of Juncus rhizomes producing new culms, b) mean fresh and mean oven dry weight of Juncus culms per plot, and c) mean length of Juncus culms.

Results and Conclusions

The results of the growth experiment (Tab. 2) show that both Juncus spp. can be cultivated on saline soil, but the growth of J. rigidus seemed to be better than that of J. acutus. This can be deduced from the following:

1. Mean number of rhizomes producing new culms was higher in case of J. rigidus (80%) than in case of J. acutus (74%);

2. Mean length of J. rigidus culms was higher (162 cm) than that of J. acutus (85 cm) culms;

3. Mean fresh weight of J. rigidus culms (4.95 kg/plot) was higher than that of J. acutus (2.81 kg/plot); and

4. Though the mean moisture content of J. rigidus culms (63.5%) was higher than that of J. acutus culms (60.23%), the mean oven dry weight of the first (1.96 kg/plot) was higher than that of the second (1.11 kg/plot).

Table 2: Results of the first harvesting of Juncus (growth) experiment at Manzala.

Date of Experiment: October 1, 1974 - October 1, 1975.

Measurements	J. rigidus	J. acutus
Mean number of rhizomes succeeded to give new culms (out of 12 rhizomes/plot)	10.46	8.95
Mean length of culms (cm)	162.00	85.00
Mean fresh weight of culms/plot (kg)	4.95	2.81
Mean oven dry weight of culms/plot (kg)	1.96	1.11
Mean moisture content of the culms (%)	63.50	60.23

Ratios Between	J. rigidus	:	J. acutus
Measurements			
Mean number of rhizomes producing new culms	1.17	:	1
Mean length of culms	1.55	:	1
Mean fresh weight of culms	1.76	:	1
Mean dry weight of culms	1.53	:	1
Mean moisture content	1.054	:	1

EXPERIMENT II: NITROGEN - PHOSPHORUS MANURINGS

Materials and Method

The experiment was extended in order to find out the effects of different fertilizers on the vegetative yield of both Juncus spp. Accordingly, and after the harvesting of experiment I, the following fertilization scheme was applied, at random, to the plots of the experiment (six replicates for each treatment):

A - Control = No addition of fertilizers
B - N_1P_1 = 20 kg N* + 25 kg P** per feddan***
C - N_2P_1 = 40 kg N + 25 kg P per feddan

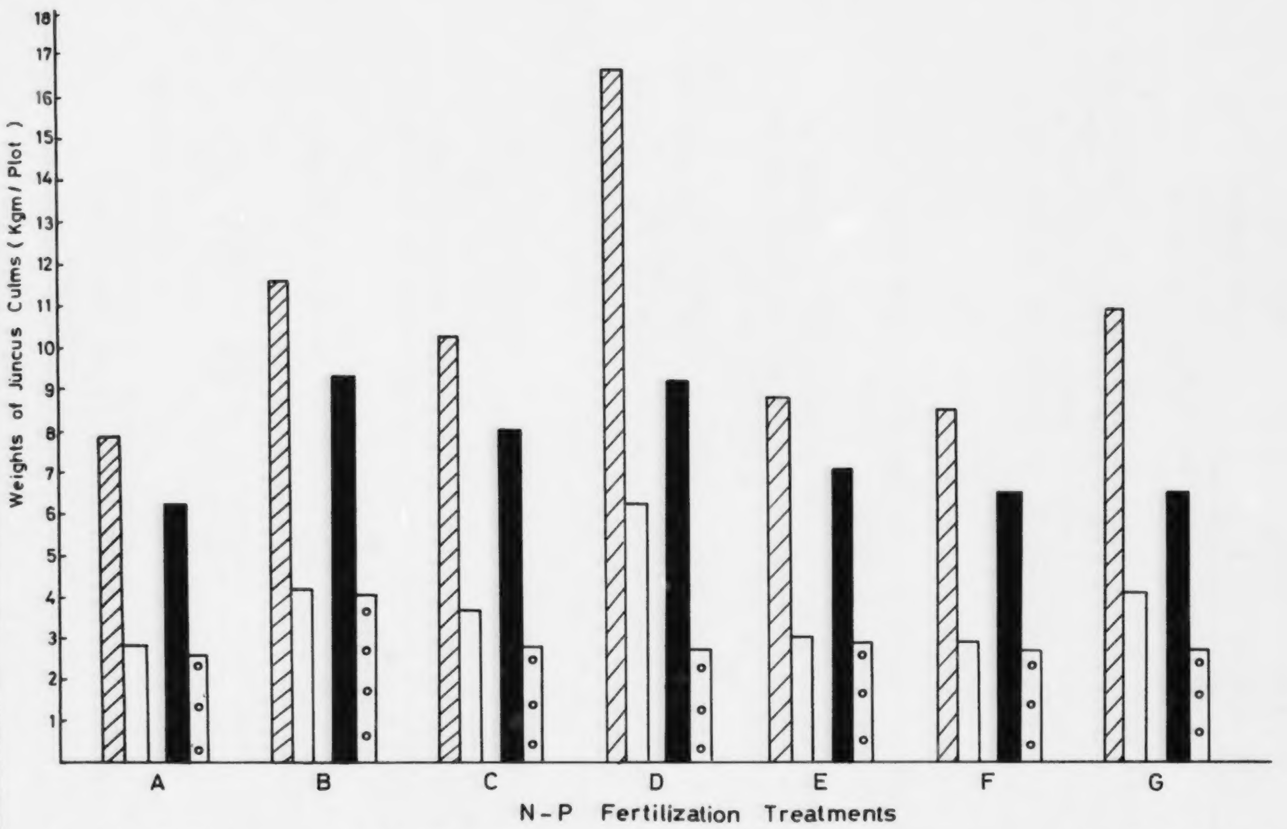

Fig (2) Histogram Showing The Fresh and Dry Weights of Juncus spp Under N-P Fertilization On Saline Soil of Manzala Lake, Egypt (Experiment II)

Legened :

▨ Mean Fresh Weight Of Juncus rigidus.
☐ Mean Dry Weight Of Juncus rigidus.
■ Mean Fresh Weight Of Juncus acutus.
○ Mean Dry Weight Of Juncus acutus.

A Control (No Fertilisation).
B $\frac{1}{2}$N + $\frac{3}{4}$P   C 1 N + $\frac{3}{4}$ P.
D 2 N + $\frac{3}{4}$ p   D $\frac{1}{2}$N + 1$\frac{1}{2}$P.   Per Plot
F 1 N + 1$\frac{1}{2}$P   E 2N + 1$\frac{1}{2}$P

D - N_3P_1 = 80 kg N + 25 kg P per feddan
E - N_1P_2 = 20 kg N + 50 kg P per feddan
F - N_2P_2 = 40 kg N + 50 kg P per feddan
G - N_2P_3 = 80 kg N + 50 kg P per feddan

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* N = $(NH_4)_2 SO_4$ ** P = P_2O_5 *** Feddan = 4,200 m^2

The plants were irrigated directly after the application of the fertilizers (October 3, 1975), thence irrigation was at weekly intervals. The experiment continued for 6 months, and the culms were harvested (second harvesting) by the end of March, 1976. The lengths of _Juncus_ spp. culms and their fresh and dry weights were measured.

Results and Conclusions

The results of the second harvesting of the _Juncus_ transplantation experiment (Tab. 3 and Fig. 2) show the following:

1. _Juncus_ spp. showed favorable growth responses to N/P fertilization as reflected by the increments in length of culms and in fresh and dry weights of the treated plots compared to the control plots.

2. In the control and fertilized plots, the fresh weights of _J. rigidus_ were higher than those of _J. acutus_ (ratio of 1:1.36). The greatest difference (6.76 kg/plot) was that of D treatment (16.8 and 9.24 kg/plot for _J. rigidus_ and _J. acutus_, respectively). Also, the lengths of _J. rigidus_ culms were greater than those of _J. acutus_ (ratio of 1:1.13).

3. Dry weights of _J. acutus_ culms were slightly lower than those of _J. rigidus_ (ratio of 1:1.15), except in D treatment in which there was 3.52 kg/plot difference between _J. rigidus_ (6.24 kg/plot) and _J. acutus_ (2.72 kg/plot). The moisture content of the culms of both spp. (63.5% for _J. rigidus_ and 60.23% for _J. acutus_) made the difference between their dry weights narrow.

4. The most favorable treatment for _J. rigidus_ was 80 kg N + 25 kg P/feddan and for _J. acutus_ was 20 kg N + 25 kg P/feddan.

5. Combination of N/P fertilizers favored the growth of _Juncus_ spp. when small amounts of P were used. The increased amounts of P added to the soil seemed to have adverse effect on the vegetative yields, as shown by yields (fresh and dry weights of the culms) of plots treated with the same amounts of N and different amounts of P fertilizers, namely: B and E, C and F, and D and G. In all cases yields decreased in the plots treated with 50 kg. P fertilizer/feddan than in the plots treated with 25 kg P fertilizer/feddan. This may

indicate that the uptake of nitrogen ions was reduced by the increased phosphorus ions in soil (antagonism). Further studies are needed to get a decisive answer.

Table 3. Results of the second harvesting of *Juncus* at Manzala.

Date of Experiment: October 3, 1975 - March 28, 1976.

N/P Fertilizers	*J. rigidus*			*J. acutus*		
	L	W		L	W	
	m	mf	md	m	mf	md
A Control	71.0	7.92	2.76	53.50	6.24	2.64
B 20 kg N + 25 kg P/F	76.0	11.52	4.20	58.70	9.36	3.96
C 40 kg N + 25 kg P/F	74.3	10.32	3.72	54.80	8.00	2.76
D 80 kg N + 25 kg P/F	75.7	16.80	6.24	60.50	9.24	2.74
E 20 kg N + 50 kg P/F	74.2	8.88	3.12	62.86	7.20	2.88
F 40 kg N + 50 kg P/F	75.5	8.64	2.95	54.69	6.60	2.64
G 80 kg N + 50 kg P/F	78.5	11.00	4.20	59.00	6.62	2.74

L = length of *Juncus* culms (cm)
W = weight of *Juncus* culms (kg/plot)
m = mean
f = fresh

d = dry
F = feddan (4,200 m^2)
N = nitrogen fertilizer $(NH_4)_2 SO_4$
P = phosphorus fertilizer P_2O_5

Ratios Between	*J. rigidus*	:	*J. acutus*
Mean length of culms (cm)	1.30	:	1
Mean fresh weight of culms (kg)	1.36	:	1
Mean dry weight of culms (kg)	1.15	:	1

REFERENCES

Boyko, H. 1966. Basic ecological principles of plant growing by irrigation with highly saline or sea-water. *In* Hugo Boyko, ed., Salinity and Aridity. Dr. W. Junk, the Hague. Chapter 2. pp. 131-200.

El-Bagouri, I., M.A. Zahran, and A. Amin Abdel-Wahid. 1976. Transplantation of *Juncus* spp. on calcareous soils, Egypt. Bull. Fac. Sci. Mansoura University. In press.

Kassas, M. and M.A. Zahran. 1967. On the ecology of the Red Sea littoral salt marsh, Egypt. Ecol. Monog., **37**:297-315.

Migahid, A. M., et al. 1955. Types of habitat and vegetation at Ras El-Hekma. Bull. Inst. Desert d'Egypt 5:107-190.

Osman, F., M.A. Zahran and S. Fayad. 1975. Potentialities of the seeds of the flora of Egypt for oil production. Bull. Fac. Sci. Mansoura University, 3:85-95.

Täckholm, Vivi and M. Drar. 1954. Flora of Egypt. Bull. Fac. Sci. University of Cairo, III. 644 pp.

Walter, H. 1961. The adaptation of plants to saline soils. *In* Salinity problems in the arid zones, Proceedings of the Teheran Symposium, UNESCO, Paris. Arid Zone Research XIV, 129-134.

Zahran, M.A. and W.A. Girgis. 1970. On the ecology of Wadi El-Natrun. Bull. Inst. Desert d'Egypte, 18:229-267.

Zahran, M.A. 1975. On the germination of seeds of *Juncus rigidus* C.A. Mey and J. *acutus* L. Bull. Fac. Sci. Mansoura University, 3:75-85.

Zahran, M.A., H. Kamal El-Din and S. Boulous. 1972. Potentialities of fiber plants of Egyptian flora in national economy. Bull. Inst. Desert d'Egypte, 22:193-202.

Zahran, M.A. 1976. On the ecology of the halophytic vegetation of Egypt. Bull. Fac. Sci. Mansoura University. In press.

FOLIAR CONTENTS OF SODIUM AND CHLORIDE ON CITRUS ROOTSTOCKS IRRIGATED WITH SALINE WATERS

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INTRODUCTION

Citrus is generally salt-sensitive, accumulating chloride and sodium in leaf tissue. While this has been pointed out in several reviews of salinity problems (Hayward and Bernstein, 1958; Bernstein and Hayward, 1958; Bernstein, 1965), it has not been studied in complete detail.

Chloride and sodium toxicity symptoms in citrus are sufficiently well-known not to require detailed description here (Bingham et al., 1969; Chapman et al., 1969). Citrus, like most fruit trees, does not develop well-defined necrotic lesions in response to low levels of chloride toxicity. Sodium toxicity causes well-defined leaf necroses, usually in more or less isolated areas along the leaf margins. However, these visual symptoms should be confirmed by leaf analysis.

Varietal differences in salt tolerance among most other crops are of secondary importance (Bernstein, 1964). In citrus, however, varietal and rootstock differences are very important. This conclusion is primarily determined by comparing the sensitivity of different citrus rootstocks to chloride and sodium toxicity and also by noting differences in ion transport rates in various rootstock varieties.

Cooper and co-workers (1951a, 1951b, 1952, 1953, 1959) show that there is a great variation in salt tolerance in relation to rootstocks studied. Salt uptake and accumulation in citrus is related to the ability of different rootstocks to exclude chlorides.

Harding and Chapman (1951) pointed out that leaf chloride content exceeding 0.25% is considered indicative of chloride toxicity.

Cooper (1961) studied the tolerance of several rootstocks in artificially salinized soils. Selectivity of citrus rootstocks determines chloride accumulation and the injury symptoms are related to the chloride content in the leaves. Among the rootstocks studied Cleopatra mandarin was one of the most tolerant.

Hewitt et al. (1965) working with plants of four different citrus rootstock irrigated with a nutrient solution of NaCl (80 me/l) showed that visual symptoms of toxicity of Cl were directly related with the accumulation of this ion in the leaves of the four varieties.

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Furr et al. (1968) noted that Valencia orange was affected when chloride contents in the leaves reached 0.5%. Higher levels in the leaves were associated with reduction in shoot development.

Chapman et al. (1969) in a study of the effects of equivalent amounts of calcium and sodium chloride (7.5, 15, 30 and 60 me Cl/l) on Washington navel orange trees on Troyer citrange rootstock found a correlation between chloride content in the saturation extract and leaves, respectively. They showed that growth was retarded and yield reduced when the chloride content in the leaves was 0.75%.

Altman et al. (1970) found a large difference in the chloride content of 11 varieties of citrus.

The present experiment studied the effect of sodium chloride in the irrigation water on foliar contents of chloride and sodium of six citrus rootstocks, with varying tolerance to salinity.

MATERIALS AND METHODS

The 15-month experiment was carried out in a greenhouse with a factorial design of 4 plots and 2 replicates. For 13 months trees were irrigated with differential treatments. In each plot (1.2 m x 1.5 m x 0.9 m) there were five two-year old trees of each variety (total of 30 trees per plot). The trees were grown in brown-calcareous soil of low fertility level. Chemical characterization of the soil is presented in Table 1.

Rootstocks used in this experiment were: Sour orange (Citrus aurantium L.), Troyer citrange (Poncirus trifoliate x Citrus sinensis), Cleopatra mandarin (Citrus reticulata blanco), Allemow (Citrus macrophylla Wester), Nanshodaidai (Citrus taiwanica) and Kinnow mandarin (Citrus nobilis Loureiro x Citrus deliciosa Tenore) which show different tolerance to salinity in germination phase (Caro et al., 1974).

Sodium chloride concentrations in the irrigation waters were gradually increased during the experiment (Table 2) to permit the plants to adjust osmotically.

During the experiment the irrigations were made every 3 to 6 weeks, adding sufficient water to restore soil moisture to field capacity. At the end of the experiment the chloride and sodium concentrations in the soil corresponded to non-saline, slightly saline, saline and very saline soils (Cerdá et al., 1976).

During the experiment, leaf samples were collected from each tree at four different times. This was done when the different salinity treatments were begun and each time that the chloride level was increased. Leaves were rinsed, oven dried at 65°C, and ground to get material for chemical analysis. Chlorides were determined potentiometrically

Table 1. Soil Analysis

Coarse sand %	20.40	CEC, me/100 g	13.12
Fine sand %	40.80	Total $CaCO_3$ %	55.00
Silt %	17.00	Active $CaCO_3$%	10.00
Clay %	21.02	Organic matter %	0.78
EC 1:5, mmhos/cm	0.11	Total nitrogen %	0.05
Chlorides, me/100g	0.05	Total sodium,me/100 g	0.65
Calcium sulfate•2 H_2O	0.01	Assimilable potassium, me/100 g	0.12
Field capacity (1/3 bar),%	17.9	Assimilable phosphorus, ppm (Olsen and Watanabe)	40

Table 2. Chloride contents in the irrigation waters

Number of irrigations at each salinity level	Salinity level (me/l)			
	0	1	2	3
1, 2, 3	1.5	1.5	1.5	1.5
4, 5, 6, 7, 8	1.5	4.5	7.5	10.5
9, 10	0.0	7.5	15.0	20.0
11, 12, 13, 14, 15	0.0	10.0	20.0	40.0

according to the method of Johnson et al. (1958). Sodium from the nitric perchloric extract (Abrisqueta et al., 1969) was measured by flame photometry.

RESULTS AND DISCUSSION

The data presented in Tables 3 and 4 show the foliar sodium and chloride contents for each rootstock, salinity level, and sampling date.

Statistical study of the results show that:

1. different rootstocks and sampling dates produced significant differences (P:0.001) in sodium and chloride of leaves, especially in the case of rootstock effect on sodium uptake;

2. differential treatments caused very significant differences (P:0.001) in foliar sodium and chloride contents;

3. significant differences in sodium and chloride were also related to rootstock-sampling date interactions (P:0.001), rootstock-saline level interactions (sodium = P:0.001 and chloride = P:0.01), and sampling date-salinity level interactions (chloride = P:0.001 and sodium = P:0.01).

The results of this study show a significant rootstock effect on uptake and accumulation of sodium and chloride.

The accumulation of chloride in the leaves of sour orange and Troyer citrange rootstocks is greater than the other rootstocks, while Cleopatra mandarin and Kinnow mandarin have the lowest values. These results are in agreement with those of Cooper (1961) and Furr and Ream (1968) which indicate that mandarins are more tolerant to salinity due to a capacity to exclude chlorides from the accumulated salts. On the other hand the response of the rootstocks to sodium accumulation differed. Kinnow mandarin showed a marked accumulation 2 to 4 times greater than the other varieties. The Nanshodaidai and Troyer citrange accumulated moderate concentrations of sodium. The Cleopatra mandarin, Allemow and sour orange accumulated small amounts of sodium.

The effect of sampling date on Na and Cl was highly significant. This was caused by increases in Na and Cl contents of irrigation waters at different sampling dates and by changes due to development of leaves throughout the period.

Rootstock-sampling date interactions were significant because the uptake of these elements by each rootstock was different during the development cycle.

Salinity level had highly significant effects on sodium and chloride contents in the leaves and shows the correlation between sodium and chloride content in the substrate and the amount of these elements taken up by the plants.

Table 3. Chloride content in leaves of citrus rootstocks (me/100 g)

Sampling date	Salinity level	S.O.	T.C.	C.M.	A	N	K.M.
1a	0	13.5	18.3	7.7	9.3	9.0	9.5
	1	13.0	20.9	8.5	10.1	9.9	12.3
	2	15.0	21.6	7.8	10.2	11.7	10.7
	3	7.1	31.2	9.1	12.4	15.7	13.9
2a	0	16.6	9.9	4.9	10.9	7.3	5.7
	1	16.4	14.7	10.3	15.2	12.5	7.4
	2	25.6	15.6	8.4	17.5	16.5	9.4
	3	28.4	25.2	6.7	21.4	21.1	7.9
3a	0	17.5	6.6	3.7	8.6	5.9	3.1
	1	18.9	13.4	3.5	15.2	11.8	4.1
	2	38.1	17.7	6.5	17.2	20.9	5.0
	3	48.8	27.5	5.4	34.3	22.7	10.4
4a	0	13.5	9.3	4.0	8.5	6.8	4.3
	1	16.7	23.1	4.5	21.7	14.4	4.7
	2	38.5	33.5	7.3	26.1	40.7	9.5
	3	59.1	55.5	5.5	28.8	50.0	15.1

Mean of Levels		Mean of Rootstocks		Mean of Sampling Dates	
Level 0	8.93	S.O.	24.17	Sampling 1a	12.85
Level 1	12.61	T.C.	21.50	Sampling 2a	13.98
Level 2	17.96	C.M	6.48	Sampling 3a	15.28
Level 3	23.47	A	16.71	Sampling 4a	20.88
		N	17.30		
		K.M.	8.31		

L.S.D.	1%	5%
Rootstocks	4.43	3.32
Sampling dates and saline levels	3.62	2.71

S.O. → Sour orange
T.C. → Troyer citrange
C.M. → Cleopatra mandarin

A → Allemow
N → Nanshodaidai
K.M. → Kinnow mandarin

Table 4. Sodium content in leaves of citrus rootstocks (me/100 g)

Sampling date	Salinity level	S.O.	T.C.	C.M.	A	N	K.M.
1a	0	2.9	6.1	4.4	3.0	4.5	14.6
	1	3.4	7.0	4.2	3.2	5.6	14.6
	2	2.9	5.2	3.7	2.5	4.7	12.0
	3	2.7	11.6	3.8	2.6	7.0	20.1
2a	0	3.3	4.1	4.9	3.8	5.2	10.2
	1	3.4	4.7	4.5	6.0	9.0	12.0
	2	4.1	4.3	4.7	4.7	9.9	13.1
	3	5.6	10.5	4.7	4.9	9.8	20.1
3a	0	2.6	3.1	2.9	3.0	3.4	5.3
	1	2.8	3.6	3.0	3.2	6.5	7.0
	2	3.8	4.0	5.2	3.9	7.2	10.6
	3	2.8	5.7	4.8	3.9	6.3	16.8
4a	0	2.4	3.7	2.8	3.8	4.0	6.3
	1	2.7	5.1	3.5	5.1	4.7	8.0
	2	3.9	5.6	4.2	4.7	7.8	15.9
	3	3.5	8.0	4.8	4.6	7.5	21.3

Mean of Levels		Mean of Rootstocks		Mean of Sampling Dates	
Level 0	4.60	S.O.	3.30	Sampling 1a	6.35
Level 1	5.53	T.C.	5.77	Sampling 2a	6.98
Level 2	6.19	C.M	4.13	Sampling 3a	5.06
Level 3	8.06	A	3.93	Sampling 4a	6.00
		N	6.44		
		K.M.	12.99		

L.S.D.	1%	5%
Rootstocks	1.03	0.77
Sampling dates and saline levels	0.84	0.63

S.O.	Sour orange	A	Allemow
T.C.	Troyer citrange	N	Nanshodaidai
C.M.	Cleopatra mandarin	K.M.	Kinnow mandarin

Rootstock-salinity level interactions were highly significant due to different response of each rootstock to the salinity level.

Chloride contents in the leaves of different rootstocks were proportional to the concentration of this ion in the respective substrates (Fig. 1). These differences were more marked at increased salt concentration in the substrate. Differences were greatest at the highest levels and show the specific response of each rootstock to the sodium chloride salinization, and it can be seen that mandarin rootstocks have the lowest values of chloride contents in the leaves. Allemow and Nanshodaidai accumulated middle values, and Troyer citrange and sour orange had the highest values. Similar results have been reported by Cooper et al. (1952, 1959, 1953, 1951a, 1951b).

Figure 1 shows also the response of different varieties to the sodium accumulation in the leaves. Kinnow mandarin accumulated approximately 2 to 4 times more sodium than the other varieties. Likewise, the accumulation of Na in the plants of the salinized plots is not proportional to the accumulation of chloride in any rootstocks.

Salinity level-sampling date interactions were highly significant for chloride (P:0.001) and sodium (P:0.01) and show the increasing uptake of both ions in the leaves with increasing levels of sodium and chloride content in the substrate.

Differences between the accumulation of chloride in the leaves when irrigation water had 20 me/l NaCl was significant at all sampling dates. On the other hand, sodium content in the leaves was not significant at different sampling dates.

Results of this experiment show that the salinization of the substrate by NaCl results in an increase in the chloride and sodium content of leaves which is characteristic for each rootstock variety studied. This showed that mandarin as a group was characterized by a marked capacity to exclude chloride ions. The Allemow and Nanshodaidai accumulated moderate concentrations of chloride ions. The sour orange and Troyer citrange varieties in general accumulated high amounts of chloride ions.

On the other hand, sodium accumulation was more irregular among the rootstocks. The Kinnow mandarin had higher values than the other rootstocks. Sodium concentration decreased in the following order: Kinnow mandarin > Nanshodaidai > Troyer citrange > Cleopatra mandarin > Allemow > sour orange.

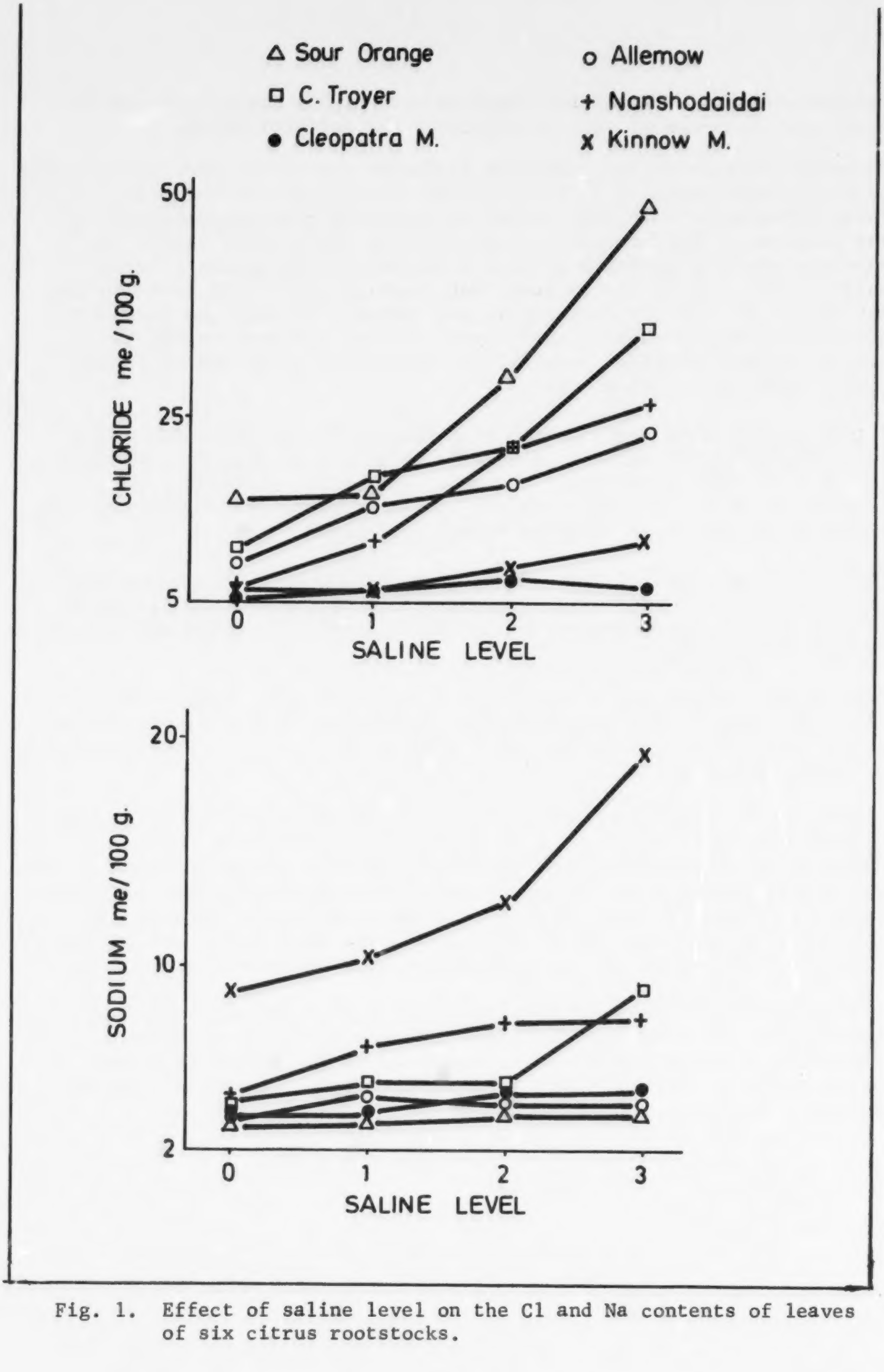

Fig. 1. Effect of saline level on the Cl and Na contents of leaves of six citrus rootstocks.

LITERATURE CITED

Abrisqueta, C., and M. Romero. 1969. Digestión humeda rápida de suelos y materiales orgánicos. An. Edafol. Agrobiol. XXVIII: 855-867.

Altman, A., and A. Goell. 1970. Chloride content of citrus seeds and its distribution in various fractions. Proc. Amer. Soc. Hort. Sci. 95:193-195.

Bernstein, L. 1964. Salt tolerance of fruit crops. USDA Infor. Bull. 283.

Bernstein, L. 1965. Salt tolerance of fruit crops. USDA Infor. Bull. 292.

Bernstein, L., and H. E. Hayward. 1958. Physiology of salt tolerance. Ann. Rev. Plant Physiol. 9:25-46.

Bingham, F. T., L. H. Stolzy, and H. D. Chapman. 1969. Effects of variable water quality on Valencia tree performance. Proc. First Int. Citrus Symp. 3:1803-1809.

Caro, M., A. Cerdá, F. G. Fernández, and M. G. Guillén. 1974. Tolerancia a la salinidad de portainjertos citricos durante la germinanción. Proc. 1973 Int. Citrus Congress I:313-316.

Cerdá, A., F. G. Fernández, and M. Caro. 1976. Efecto del cloruro sódico en el agua de riego sobre la suculencia foliar de portainjertos citricos. Anal. Edaf. Agrob. (en prensa).

Chapman, H. D., H. Joseph, and D. S. Rayner. 1969. Effects of variable maintained chloride levels on orange growth, yield and leaf composition. Proc. First Int. Citrus Symp. 3:1811-1817.

Cooper, W. C. 1961. Toxicity and accumulation of salts in citrus trees on various rootstocks in Texas. Proc. Fla. Hort. Soc. 74:95-104.

Cooper, W. C., and B. S. Gorton. 1952. Toxicity and accumulation of chloride salts in citrus on various rootstocks. Proc. Amer. Soc. Hort. Sci. 59:143-146.

Cooper, W. C., and A. Peynado. 1959. Chloride and boron tolerance of young lime citrus trees on various rootstocks. Proc. Rio Grande Valley Hort. Soc. 13:89-96.

Cooper, W. C., and A. V. Shull. 1953. Salt tolerance and accumulation of sodium and chloride ions in grapefruit on various rootstocks grown in a naturally saline soil. Proc. Seventh Annual Rio Grande Valley Hort. Inst., p. 46-52.

Cooper, W. C., B. S. Gorton, and C. Edwards. 1951a. Salt tolerance of various citrus rootstocks. Proc. Fifth Annual Rio Grande Valley Hort. Inst. 46-52.

Cooper, W. C., B. S. Gorton, and E. O. Olson. 1951b. Ionic accumulation in citrus as influenced by rootstocks and scion and concentration of salts and boron in the substrate. Plant Physiol. 27:191-203.

Furr, J. R., and C. L. Ream. 1968. Shoot growth of Valencia orange in relation to salinity and salt accumulation. Proc. Amer. Soc. Hort. Sci. 93:153-158.

Harding, R. B., and H. D. Chapman. 1951. Progress report on a study of soil characteristics in forty high-performance orange orchards in California. Soil Sci. Soc. Amer. Proc. 15:243-248.

Hayward, H. E., and L. Bernstein. 1958. Plant-growth relationships on salt-affected soils. Bot. Rev. 24:584-635.

Hewitt, A. A., and J. R. Furr. 1965. Influence of salt source on the uptake of chlorides by selected citrus seedlings. Proc. Amer. Soc. Hort. Sci. 86:201-204.

Johnson, C. M., R. P. Houston, and P. G. Ozanne. 1958. Measurement of microgram amounts of chlorine in plant materials. Agric. Food Chem. 6:114-118.

IRRIGATION WITH SALINE WATER UNDER DESERT CONDITIONS

A. Hardan [1]

INTRODUCTION

Due to the development in urban and agricultural areas, and to the neglect of the desert regions, the gap in education, health, social welfare, and standard of living between the population of the desert region and the inhabitants of urban and agricultural areas widens rapidly. In recent years the Government of Iraq, possessing the political will to invest in the infrastructure which will service agriculture, has taken a keen interest in developing the desert regions of Iraq and in improving the living conditions of their population.

Several research/demonstration stations have been developed in the Western Desert of Iraq servicing an area of over 80,000 m^2. The overall objective of the desert development program is to provide for more comforts, more stable food and water supplies, improved diets, and improved health and educational services for the desert dwellers, without abrupt changes in their life style. In other words, to establish an improved desert community by creating an artificial oasis through the development of available groundwater in conjunction with captured surface water. The planning and distribution of these oases are designed to reduce the risk of heavy losses of livestock caused by long and severe drought periods, to reduce overgrazing in certain areas and thus improve their natural vegetation, to reduce the plowing of marginal lands and thus reduce soil erosion, and to act as a nucleus for the development of desert communities.

Throughout the stages of the desert development program, emphases are placed on the full understanding and evaluation of the traditional conditions and potentials of the desert resources and population. Thus the desert dwellers are fully and actively participating in the programing, establishing, and utilizing of the development schemes within their regions.

The destructive activities of mankind in many parts of the world are well recognized: the major climatological and environmental changes of drought, flooding, pollution, diseases, and natural catastrophies; the generous use of the rich natural resources; and the presence of many millions of the world's people who are in need of food and the others who fear a future need. We have directed a major part of our applied research activities to investigate the technical, practical, social, and economic feasibility of utilizing marginal resources for agricultural development in the less fortunate areas. Among such studies is the selection and demonstration of suitable management practices for different crops, waters, and soils under desert conditions.

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This paper reports some of the technical results from irrigating pear trees, wheat, and potatoes with saline water in the Western Desert of Iraq.

MATERIALS AND METHODS

Experiments were carried out at the central station for desert development in the Western Desert of Iraq. The station is located about 60km west of the town of Haditha at an elevation of 320 m above sea level.

The general climatic feature of the area is dry and hot summers followed by mild winters and low precipitation. The average annual rainfall is 100 mm occurring between the months of October and May. The mean annual air temperature is 19-23°C with the mean temperature of 7-10°C in January and 30-35°C in July. Throughout the year westerly winds are prevailing, with the highest average monthly wind speeds usually occurring in July. For summer months a considerable fluctuation in daily wind speed is typical, i.e., from 2-3 m/sec at night to 5-6 m/sec at noon. The annual mean relative humidity is 38 percent (from 15 percent in July to 69 percent in December and January). The highest monthly pan evaporation is 824 mm during July and the lowest is 103 mm during January.

Typical natural features are as follows: Soil order is Aridosol, great soil group is Lithic Calciorthids, climate is arid, the soil is moderately deep over parent material of secondary gypsum on limestone bedrock, natural vegetation is nill, elevation is 320 m above sea level, relief is nearly level, permeability is moderate, drainage is good, water table is deeper than 100 m, water holding capacity is moderate, human influence is nill, biological activity is low, salt and alkali are slight, and wind erosion is severe.

A typical soil profile has the following characteristics:

Depth (cm)	Description of Profile
0 - 30	Pink (7.5 YR 7/4 dry) or strong brown (7.5 YR 5/6 moist) clay loam, weak fine to very fine subangular blocky breaking to single grain, slightly hard, slightly sticky, common fine vesicular pores, very few fine roots, abrupt wavy.
30 - 60	Pink (7.5 YR 7/4 dry) or reddish yellow (7.5 YR 6/6 moist) sandy clay loam, massive breaking to single grain, highly gypsiferous, slightly hard, nonsticky, nonplastic, few limestone rocks, clear wavy.
60+	Secondary gypsum on broken hard limestone bedrock.

The electrical conductivity (EC) of the saturation extract of the surface soil (0 - 30 cm) is 2.6 mmho/cm and for the subsoil is 4.1 mmho/cm; gypsum is 0.65 percent; lime is 51.2 percent; CEC is 12.0 me/100g; organic matter is 0.7 percent; and exchangeable sodium percentage is 5.0.

Groundwater pumped from a depth of 190 m and containing about 4000 ppm soluble salt was used for irrigation as one of 3 water qualities. Harvested rainwater was utilized to dilute the groundwater to 2000 ppm and 500 ppm soluble salt, respectively, as the second and third water qualities for this experiment. The main chemical components (in ppm) of the groundwater were: Total soluble salt = 3986; calcium = 290; sodium = 338; magnesium = 125; potassium = 37; sulfate = 472; chloride = 1040; bicarbonate = 208; nitrate = 5; copper, zinc, manganese, and molybdenum each < 0.05; aluminum < 0.5; iron = 0.3; and boron < 0.1. The pH was 6.7.

Among the many forest trees, fruit trees, field crops, and vegetables which have been tried on a large scale in the several stations, pear trees, wheat, and potatoes were selected for this experiment. The same water qualities (4000 ppm, 2000 ppm and 500 ppm soluble salt) were used to irrigate the three crops in five replicates and for three seasons. The amount of water used to irrigate all treatments was determined by soil sampling and observation of evaporative conditions.

Five rows of newly planted pear trees (ten trees in each row) with spacing of 5 m between rows and 4 m between trees were irrigated with each water. Trickle irrigation was used with spot - spitter emitters of 0.22 gallon/ minute discharge and the soil surface for each tree was mulched with a 10 cm layer of local gravel. All trees were irrigated with the respective waters 2 to 3 times a week. Seasonal measurements of the tree height and circumferences of trunks at the soil surface and at mid-height were made.

Five plots of wheat (5 x 10 m each) were irrigated with each water by using sprinklers 2 to 3 times each month. Grain yields were recorded.

Five rows of potatoes (each 25 m long) were irrigated with each water. Furrow irrigation was used 3 to 4 times each month and potato yields were recorded.

Statistical analyses were made on the seasonal growth and yields for three seasons, and seasonal soil sampling was carried out to characterize salinity changes due to irrigation.

RESULTS AND DISCUSSION

Statistical analyses showed no significant reduction in the growth of newly planted pear trees as a result of irrigation with saline water for 3 years. The highest level of water salinity (4000 ppm) is considered too high for irrigation by all standards of water quality classification (Branson et al., 1975; FAO,1971; FAO/UNESCO,1973; U. S. Salinity Lab. Staff, 1954). In many parts of Iraq, irrigation has been carried out for centuries with water having 5g of dissolved solids per liter (UNESCO,1956). Farming system and management practices are believed to be the key factors in achieving successful results. In this experiment, among the practices that helped obtain good results were the irrigation method and mulching of the wetted soil surface. Under these practices, although the amount of irrigation water per tree was reduced by 50 percent as compared to conventional methods of furrow or basin irrigation, the soil moisture within the root zone was always at or near field capacity.

The direction of water flow was always towards the drier soil beyond the boundaries of the root zone and thus the salt accumulation is mostly within the narrow band of the wetting front. Therefore, the salinity of the soil solution within the active root zone was in equilibrium with that of the irrigation water or lower due to precipitation of lime and gypsum within the soil system (Hardan, 1969).

Table 1 shows the vertical and horizontal distribution of salinity within the wetted soils around the trees, with and without gravel mulching.

Table 1. Soil salinity (E_{ce}) at different soil depths and distances from the trunk after three years of irrigating pear trees with 4000 ppm water.

Soil Depth	Distance from tree trunk							
(Cm)	30 cm		60 cm		120 cm		Wetting front	
	Mulch	No mulch	Mulch	No Mulch	Mulch	No Mulch	Mulch	No Mulch
0-10	2.85	4.10	3.00	4.32	3.36	6.74	4.60	9.32
10-50	3.07	3.05	3.28	3.60	3.14	4.05	4.23	6.04
50-75	4.13	4.06	3.92	3.92	3.85	4.46	5.57	4.88

The data show slight and continuous increase in soil salinity as the distance increased from the tree trunk towards the wetting front in the presence of mulch, whereas the increase in salinity was much greater where no gravel mulch was used. The salinity level of the top 10 cm soil without mulch was more than twice that with the gravel mulch. Soil salinity always slightly increased with depth under the mulch but where no mulch was used the soil salinity was highest at the surface 10 cm.

The analysis of variance for the effect of irrigation with saline water on the yield of wheat for three Seasons showed no statistical significance. The average yield was 2115 kg/hectare, which is parallel to that of irrigated wheat in Iraq and more than twice the average yield in the area. Using sprinkler irrigation in this experiment has reduced the applied water by 20 percent as compared to conventional basin and border irrigation. The accumulation of salinity within the root zone was never more than twice that of the irrigation water (Table 2). The growing season for wheat coincides with the rainy season, which reduced the damage from sprinkling with saline water. Using sprinklers with the same saline water to irrigate summer crops has been shown to be very damaging and not feasible.

Table 2. Soil salinity (E_{ce}) at different depths after three seasons of irrigating wheat and potatoes with 4000 ppm water

Soil Depth (cm)	EC_e (mmho/cm)	
	Wheat	Potatoes
0 - 10	3.65	6.48
10 - 30	3.20	5.60
30 - 60	4.82	5.85

There was a significant reduction (23 percent) in the yield of potatoes when irrigated with 4000 ppm water. Irrigating with this water has raised the soil salinity (EC_e) of the top 10 cm to 6.48 mmho/cm after three growing seasons. According to the predicitions of the U. S. Salinity Laboratory (1), these levels of water and soil salinity should cause more than a 50 percent reduction in the yield of potatoes. It is believed that this disagreement is mostly due to the differences in the experimental conditions, since California's research on salt tolerance of plants is usually carried out under controlled or suitable conditions and not under desert conditions.

REFERENCES

Branson, R. L. et al. 1975. Water quality in irrigated watersheds. J. Environ. Qual. 4:33-40.

FAO. 1971. Salinity Seminar, Baghdad. Irrigation and Drainage Paper No. 7.

FAO/UNESCO. 1973. Irrigation, Drainage, and Salinity. An International Sourcebook. Unesco, Paris/Hutchison and Co., London. 510p.

Hardan, A. 1969. Centennial Publication. The American University of Beirut. p. 409-441.

UNESCO. 1956. Utilization of Saline Water. Reviews of Research. Arid Zone Research IV.

U. S. Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. U. S. Department of Agriculture Handbook No. 60.

PREDICTED AND ACTUAL YIELD DECLINE FROM FIFTY PERCENT INCREASE IN SALINITY OF THE COLORADO RIVER [1]

Frank E. Robinson [2]

INTRODUCTION

There is a considerable body of data available treating crop yield declination as a function of water salinity. Many of these data have been summarized in a report by the University of California Committee of Consultants (1974) based upon USDA Agricultural Information Bulletin 283 and personal communications with Leon Bernstein, USDA Salinity Lab., Riverside, California.

Projections of crop yields based upon the Committee of Consultants data may not be accurate if crop and irrigation conditions are different from those prevailing when the projections were made. The different conditions include the following: (1) newly developed cultivars tested in the areas of increasing salinity may have a higher tolerance of salinity - even different cultivars may show a significant difference in their response to salinity; (2) the yield declination data were derived with surface irrigation, whereas the researcher may need information for sprinkler irrigation; and (3) ion mixes used in the U. S. Salinity Laboratory contained a higher ratio of NaCl than the Colorado River water and might have exhibited more detrimental effects than the Colorado water. A 50% increase in the salinity of the Colorado River water from the present 877 ppm (EC_w = 1.35 mmho/cm) to 1,350 ppm (EC_w = 2.0 mmho/cm) projected for the 21st century falls generally within the lowest-effect range and could be compensated by higher salt tolerance of a new cultivar, more efficient water application, or a less harmful ion mix, and could be masked by the normal variation in field yields.

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The objectives of this study were to (1) determine the yields of several major crops of the lower Colorado River Basin when sprinkler irrigated with 877 ppm water and with 1,350 ppm water and (2) compare the actual field yield declination to the yield declination predicted by the criteria presently utilized by the Committee of Consultants.

PROCEDURE

Yield predictions of onion, cabbage, carrot, alfalfa, wheat, and beans were determined from linear correlations derived from crop tolerance and leaching requirement tables from Guidelines for Interpretation of Water Quality for Agriculture by the California Committee of Consultants, 1974. Six plots, 2.13 m wide and 12.2 m long, of Granex 33 and Early Premium onion, Copenhagen Market cabbage, Imperator 58 carrots, UC 76 alfalfa, Cajeme 71 wheat, and Green Crop beans were irrigated with the present 877 ppm irrigation water and six plots with water raised to 1,350 ppm. (Na^+, 10.5 meq/l; Mg^{++}, 4.4; Ca^{++}, 6.3; $SO_4^=$, 10.3; Cl^-, 7.6; and HCO_3^-, 3.3). The water was salinized by additions of $NaHCO_3$, NaCl, $MgSO_4$, and $CaSO_4$ from concrete tanks containing concentrated solutions that fed into the irrigation pump sump.

The irrigation interval and quantity were based upon irrigation applications equal to 90% evaporation from a Class A Weather Bureau pan and an available moisture storage of 10 cm. Each treatment had 3 plots located on an Imperial clay and 3 on a Meloland sandy clay loam. Each treatment had the same quantity of water applied, the same fertilization, time of planting, seed lot, cultivation, weed control, and harvest date.

RESULTS

Table 1 presents comparisons of predicted and actual yield declinations together with r^2, standard errors of estimate and calculated Fisher F test of significance for the measured yield data. The r^2, standard error of estimate and F tests are given also for the prediction equation but do not represent the original measured data. They are presented only to indicate the closeness of fit between the Committee of Consultants data and the linear equation used to represent these data.

Onion yields can be used to illustrate how Table 1 is to be interpreted.

The onion yield prediction equation, as given by the Committee of Consultants, is: $Y = 114.3 - 17.4\ x$, where Y is percent of potential yield and x is electrical conductivity of the irrigation water in mmhos/cm. The range of x, for onions, is from 0.9 to 2.7 mmhos. Irrigation water conductivities below 0.9 mmhos are considered to have no effect on onion yields.

The regression equation for actual yields of Granex 33 onions in 1974 is: $Y = 88.8 - 16.4\ x$, with a coefficient of determination (r^2) of 49.0, a standard error of estimate of 5.96, and a Fisher "F" level of 0.010. Predicted yields were 90.8 and 79.7% of the potential maximum, for irrigation water salinities of 1.35 and 2.0 mmhos/cm, respectively. Actual yields

Table 1. Prediction equations of yield declination from California Committee of Consultants data and actual field yiel T/ha of six crops grown at 877 ppm (1.35 mmho/cm) and 1,350 ppm (2.0 mmho/cm).

							Yield		
Crop	Data source	Year	Covariance equation* Y predicted = %, Y crop = T/ha, X = mmho/cm	r^2 %	Std err estimate	Fisher F level	1.35 mmho % or T/ha	2.0 mmho % or T/ha	Declination %
Onion	Predicted		Y = 114.3 - 17.3 X	98.4	2.3	0.005	90.8%	79.7%	12.3
	Granex 33	1974	Y = 88.8 - 16.4 X	49.0	5.96	0.010	66.7 T	56.0 T	16.0
	"	1976	Y = 57.5 - 8.4 X	35.9	3.99	0.050	46.2 T	40.7 T	11.8
	Early Premium	1974	Y = 51.6 - 5.7 X	30.8	3.03	0.061	44.0 T	40.3 T	8.4
	"	1976	Y = 39.3 - 3.6 X	13.9	3.18	0.230	34.4 T	32.1 T	6.8
Wheat	Predicted		Y = 126.9 - 8.1 X	99.1	3.51	0.005	100%	100%	0
	Cajeme 71	1975	Not significant				3.6 T	3.5 T	2.7
	"	1976	Y = 8.08 - 0.74 X	25.1	0.46	0.097	7.07 T	6 59 T	6.8
Beans	Predicted		Y = 119.8 - 31.0 X	98.1	3.71	0.005	77.9%	57.8%	25.8
	Green Crop	1974	Y = 5.24 - 1.61 X	38.9	0.72	0.038	3.07 T	2.02 T	34.1
Cabbage	Predicted		Y = 113.8 - 13.8 X	99.6	1.65	0.005	95.2%	86.3%	9.4
	Copenhagen Mkt	1974	Y = 78.6 - 6.87 X	19.0	5.05	0.157	69.3 T	64.9 T	6.4
Carrots	Predicted		Y = 116.0 - 24.5 X	99.7	1.41	0.005	83.0%	67.1%	19.2
	Imperator 58	1974	Y = 45.70 - 2.72 X	3.51	5.08	0.429	42.0 T	36.6 T	12.9
	"	1976	Y = 49.19 - 8.54 X	40.12	3.71	0.027	37.7 T	32.1 T	14.7
Alfalfa	Predicted		Y = 155.6 - 12.4 X	99.9	0.71	0.005	98.9%	90.8%	8.1
	UC 76	1974	Not significant				29.6 T	29.1 T	1.7
	UC 76	1975	Y = 27.4 - 2.77 X	10.1	2.95	0.31	23.6 T	21.8 T	7.6

In the prediction equations onion $0.9<x<2.7$, wheat $3.1<x<9.3$, beans $0.7<x<2.3$, cabbage $1.1<x<4.7$, carrots $0.7<x<2.7$, alfalfa $1.3<x<5.3$.

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were 66.7 and 56.0 metric tons/hectare. The predicted yield declination when irrigation water salinity was increased from 1.35 to 2.0 mmhos is 12.3%; the actual yield declination due to the increased irrigation water salinity was 16.0%. In 1976, actual Granex 33 yields decreased by 11.8%, compared to the predicted 12.3%.

UC 76 alfalfa yields in 1974 and Cajeme 71 wheat yields in 1975 were not affected significantly by the higher irrigation water salinity and, therefore, no regression equation is shown.

DISCUSSION

Referring to Table 1, the crops can be divided into group 1, with predicted yield declines averaging greater than 10%, and group 2, with less than 10% yield decline predicted. The first group contains the onions, beans, and carrots. The second group the wheat, cabbage, and alfalfa. The r^2 values (indicating the percentage of variation explained by the regression function) that were 30% or higher all fell within the group 1. The standard errors of estimate that were smaller than the difference between the yields from the two different salinities all fell within group 1.

Group 2, with projected yield declines of less than 10%, was characterized by r^2 of less than 30%, standard errors of estimate larger than the treatment differences, and F values larger than 6%. It was probable that where predicted yield declinations were less than 10%, the normal yield variation in field plot culture was greater than that due to salinity and masked the result. Where the variation in yields was unusually large in group 1, the salinity regression was also masked as in the Earl Premium onion 1976 and the 1974 carrot data.

CONCLUSION

1. When using the Committee of Consultants data to predict yield declination due to an increase from 877 to 1,350 ppm in the irrigation or from 1.35 to 2 mmho/cm conductivity, only the yield declinations of 10% or greater could be demonstrated significantly. Yield declination data from crops with a predicted loss of less than 10% exhibited r^2 values less than 30%, standard errors of estimate greater than the treatment differences, and Fisher F values greater than 6%.

2. When using linear equations based upon the California Committee of Consultants data for Colorado River water salinity, the yield declination was within 10% of the predicted value where the yield declination was 10% or greater, and the normal variation was not sufficient to mask the significance of the salinity effect.

3. Values of yield declination obtained from the Committee of Consultants gave results in an acceptable order of magnitude in waters of the Colorado River for carrots, onions, beans, alfalfa, wheat, and cabbage.

4. Different cultivars of onions showed a different tolerance to salinity change in irrigation water.

5. The declination in yield due to increase in irrigation water is of the same order of magnitude when comparing the sprinkler irrigated plots of this study to the predicted yield declinations from the Committee of Consultants data.

LITERATURE CITED

University of California Committee of Consultants. 1974. Crop Tolerance and Leaching Requirement Tables. Cited in Agricultural Extenstion Letter, Robert S. Ayers and Roy L. Branson, Davis, Cal., January 7, 1974, p. 2-5.

DISTRIBUTION AND SEASONAL VARIABILITY OF MICRONUTRIENTS IN CERTAIN SALT AFFECTED SOILS OF NORTHERN GREECE

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INTRODUCTION

Micronutrients, except boron, have received little attention in salt affected soils, which is quite understandable since the main problems in the salt affected soils do not arise from micronutrients. Little attention has also been given to the effect of salinity on the micronutrient status of certain plant species (Hassan et al., 1970a and 1970b; Maas et al., 1972).

In the reclamation of salt affected soils, leaching with large amounts of water or addition of various amendments in relatively large quantities may result in considerable losses or gains of micronutrients for the soil.

In the present work depth distribtuion and seasonal variability of boron, copper, manganese, zinc and iron, together with the distribution and variability of salts, for two areas of salt affected soils of northern Greece is examined in order to get some idea as to how leaching affects micronutrient level.

MATERIALS AND METHODS

Soils

The soil samples were collected from two areas of northern Greece, namely the areas of Lantza and Klidi near Thessaloniki.

Lantza was a lake which was drained about 20 years ago. Most of the soils are very heavy in texture, calcareous with structural B horizon, gray to dark gray colors, and a gley horizon at a depth of 1.1 - 1.5 m. The pH of the soils ranges between 8 and 9.5. The salinity is usually low at the surface horizon (4 mmhos/cm) and higher for the horizons below, while exchangeable sodium percentage is, in general, very high. The prevailing clay minerals, identified by X-ray diffraction, were kaolinite, illite, and montmorillonite.

The soils at Klidi are recent alluvial deposits close to the sea, and some of them are below sea level. They are calcareous and, although their texture varies, most of them are heavy, with gray as the prevailing color. The internal drainage is poor and the depth of the gley horizon, being about 50 cm near the sea, increases with the increase of the distance

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from the sea. The salinity is very high and it decreases with the distance from the sea, which is mainly due to the NaCl present. The prevailing clay minerals identified by X-ray diffraction, were kaolinite, illite, montmorillonite and vermiculite.

The collected soil samples were air dried, sieved through a 2 mm sieve, and then used for analyses.

It should be noted that in both areas reclamation work had started at the time of sampling, and both selected profiles were located about 6 meters away from a drainage channel.

Methods

Generally accepted methods for both the extraction and the determination of the elements were used. Cation exchange capacity (CEC) was determined by the method of Bower, Reitemeier, and Fireman (1952) while exchangeable sodium and potassium were determined from the difference between extractable in NH_4Ac and water soluble (saturation paste). In the extract, Na and K were determined by a Beckman DU flame spectrophotometer with a photomultiplier attachment. As to conductivity, it was measured in the extract of the saturation paste using conductivity bridge Model RC 216 B2, Industrial Instruments Inc. With respect to micronutrients Cu, Mn, Zn, and Fe, they were extracted in 0.05 M EDTA at pH 7.0 (Henriksen and Jensen, 1958; Viro, 1955) and determined by a Perkin-Elmer 303 Atomic Absorption Spectrophotometer. Boron was extracted in hot water and determined colorimetrically in boron-free glassware using the carmine method of analysis (Callicoat and Wolszon, 1959).

RESULTS AND DISCUSSION

Data regarding depth distribution and seasonal variability of salinity, boron, copper, manganese, zinc, and iron and also depth distribution of exchangeable sodium percentage (ESP) are presented in Figures 1-12.

The salinity is relatively low throughout the profile in Lantza (Figure 1) and lower than 4 millimhos per centimeter for the top horizon with evidence of salt leaching during the rainy period (fall to spring). Exchangeable sodium percentage however, is still quite high, and in the lower horizons (below 45 cm) it is extremely high. The salinity in Klidi (Figure 2) is, on an average, higher than that of Lantza, and salt leaching during the rainy period is more evident. Exchangeable sodium percentage is high throughout this profile.

Data regarding hot water extractable boron are given in Figures 3 and 4. The boron level in the profile of Klidi is higher than that of Lantza, which would be normally expected as the soils under study in Klidi are near the sea. As to the meaning of the obtained specific values of hot water extractable boron, the available compiled data in the literature (Bingham, 1973; Bradford et al., 1967) indicate levels of hot water extractable

FIG. 1-LANTZA

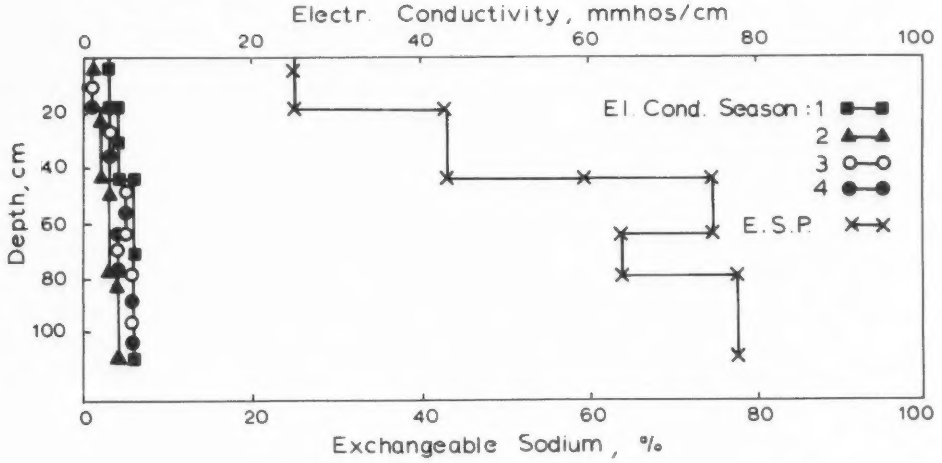
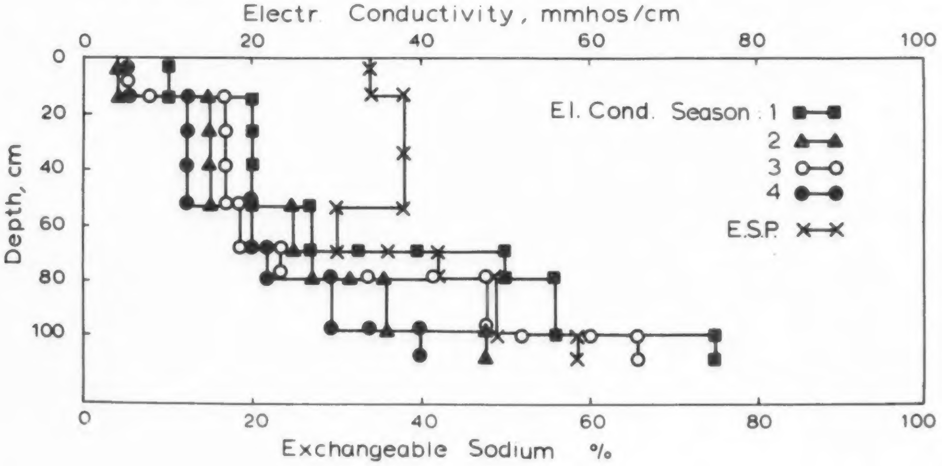


FIG. 2-KLIDI



Figures 1 and 2. Depth distribution of salts as affected by the time of sampling (season 1 = sampling on Sept. 7, 1974; season 2 = sampling on Dec. 18, 1974; season 3 = sampling on Feb. 12, 1975; season 4 = sampling on June 6, 1975) and depth distribution of exchangeable sodium percent.

boron below which deficiency symptoms are observed for various crops. They also indicate levels where various plant species grow well. General farm crops usually do not require more than 0.5 ppm of hot water extractable boron, while beets require 1 ppm or more and levels below 0.4-0.5 ppm indicate deficiency symptoms to various crops. On the basis of the above information the boron levels in the soils under consideration are high and probably toxic to various plant species, depending on their relative tolerance to this element. Regarding seasonal variability of boron, on the basis of the above data, one could say that there is some evidence of boron leaching during the rainy season.

FIG. 3-LANTZA

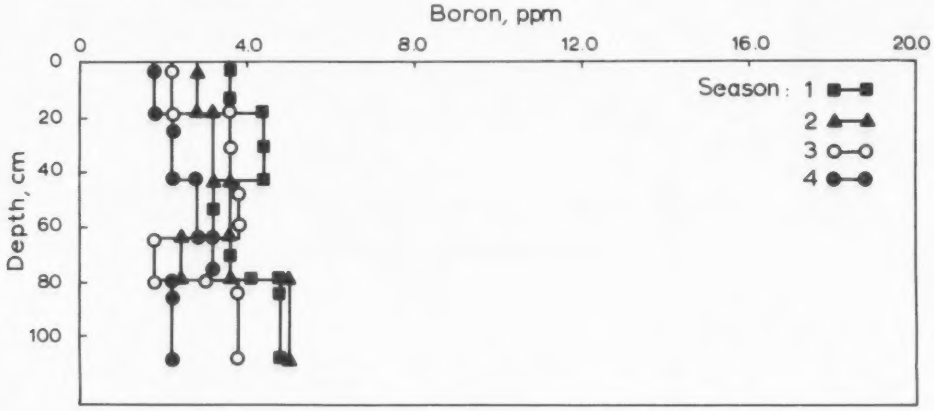
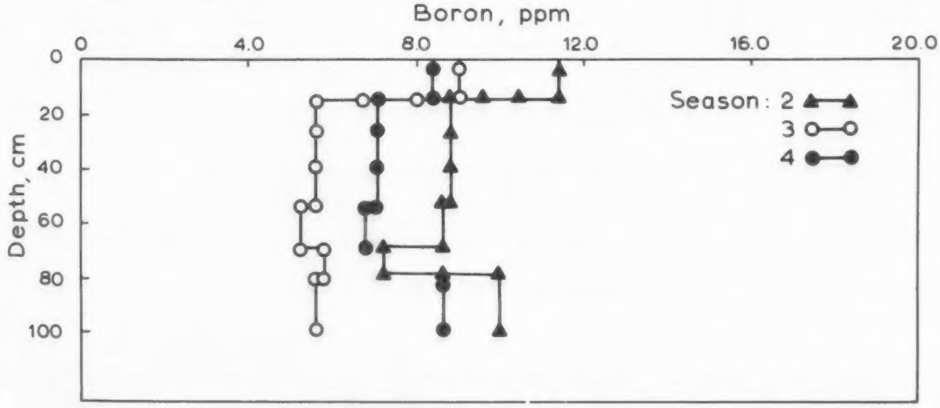


FIG. 4-KLIDI



Figures 3 and 4. Depth distribution of hot water extractable boron as affected by the time of sampling (season 1 = sampling on Sept. 7, 1974; season 2= sampling on Dec. 18, 1974; season 3 = sampling on Feb. 12, 1975; season 4 = sampling on June 6, 1975).

The levels according to depth and seasonal variability of extractable copper are presented in Figures 5 and 6. Incidentally the levels of extractable copper are similar for both profiles. As to the value of these data, most of the data available (Reuther and Labanauskas, 1973) give levels of total copper in the soil or levels of copper extractable in various solutions such as concentrated nitric acid, hydrochloric acid at pH 2.0, dithizone, etc. In normal soils the concentration of total

FIG. 5-LANTZA

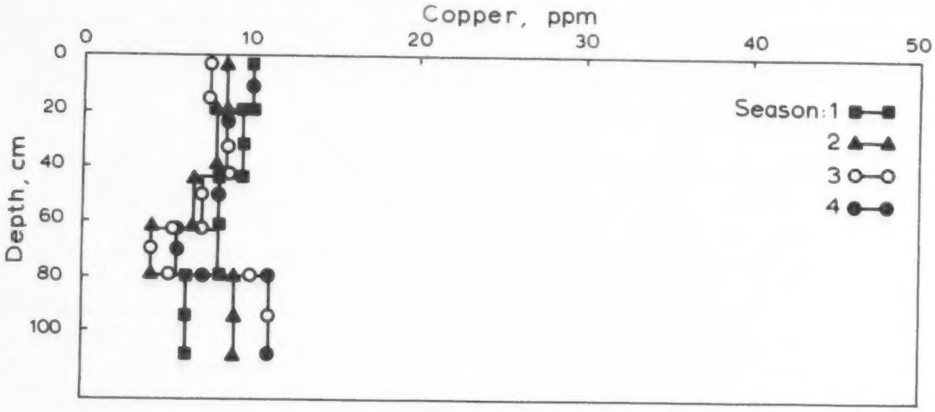
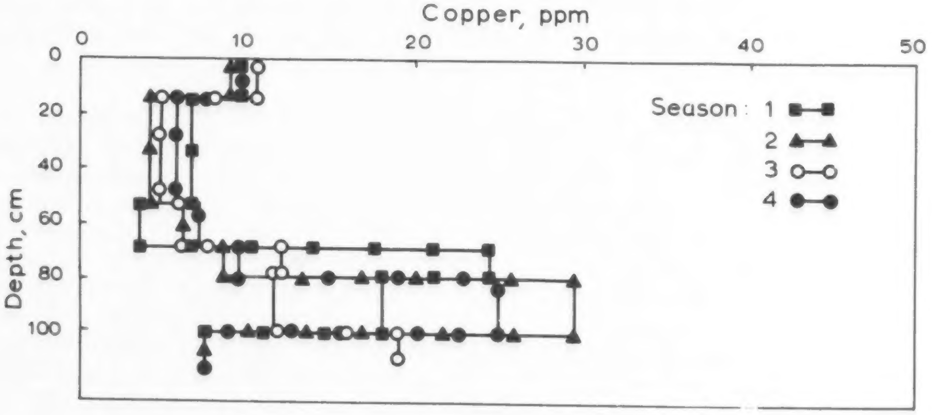


FIG. 6-KLIDI



Figures 5 and 6. Depth distribution of EDTA extractable copper as affected by the time of sampling (season 1 = sampling on Sept. 7, 1974; season 2 = sampling on Dec. 18, 1974; season 3 = sampling on Feb. 12, 1975; season 4 = sampling on June 6, 1975).

copper ranges between 2 and 100 ppm while that of EDTA extractable between 0.1 and 10 ppm, with the deficiency level for cereals being about 0.6 ppm (Mitchel, 1964). On the basis of these data the observed values of EDTA extractable copper are most probably in the normal levels. Earlier investigations on certain soil types of normal soils of Greece and Cyprus (Apostolakis and Douka, 1970; Pagel and Prasad, 1971) reported levels of copper extractable in 1% versenate as available copper; those were lower than the levels presented here. Regarding depth distribution of copper is these profiles, unpublished analytical data in our laboratory indicate a correlation between EDTA extractable copper and organic matter content for soil samples derived from both of the above areas under consideration. The seasonal variability of copper is not large, although there is some evidence of copper leaching from the upper part of the profile during the first part of the rainy season.

Extractable manganese levels, distribution, and variability are presented in Figures 7 and 8. The level of extractable manganese in Lantza was higher than that of Klidi. As to the meaning of these figures, again, the available literature data (Labanauskas, 1973; Bradford et al., 1967; Pagel and Prasad, 1971) indicate levels of total, exchangeable, easily reducible, available, etc. manganese. The normal concentrations of total manganese in soils varies between 200 and 3000 ppm (Labanauskas, 1973; Mitchell, 1964). As to the EDTA extractable manganese, deficiency symptoms can be expected in neutral to alkaline soils when EDTA extractable manganese is below 50 ppm. For acid soils the border line is lower (Hammes and Berger, 1960; Ure and Berrow, 1970). On the basis of the above information the obtained values for EDTA extractable manganese are probably low, taking into consideration that the soils in both sites are calcareous and their pH is quite high. With respect to the seasonal variability of manganese the above data are rather inconclusive.

Figures 9 and 10 give data regarding distribution and variability of zinc. Incidentally the levels are similar for both studied profiles. Some zinc accumulation on the surface layer of Klidi is probably due to its organic matter. With regard to the significance of these findings the available data in the literature (Bradford et al., 1967; Chapman, 1973; Mitchell, 1964) give total zinc or zinc extractable to various solutions such as 0.1 N $MgSO_4$, cold 1N KNO_3, etc. It is thus rather difficult to draw any definite conclusions. However, the normal total zinc concentrations are considered to be 10-300 ppm (Bradford et al., 1967; Chapman, 1973). Furthermore, total contents in the range of 10 to 200 ppm zinc gave EDTA extractable zinc of 0.4-40 ppm (Mitchell, 1964). Considering that the pH of both sites is high, the above suggest that the levels of zinc in the sites under study are probably low. In earlier work the levels of dithizone-extractable or available zinc were also low for certain soil types of Greece and Cyprus (Apostolakis and Douka, 1970; Pagel and Prasad, 1971). As to seasonal variability the data indicate some leaching from the upper part of the profile during the late part of the rainy season.

FIG. 7 - LANTZA

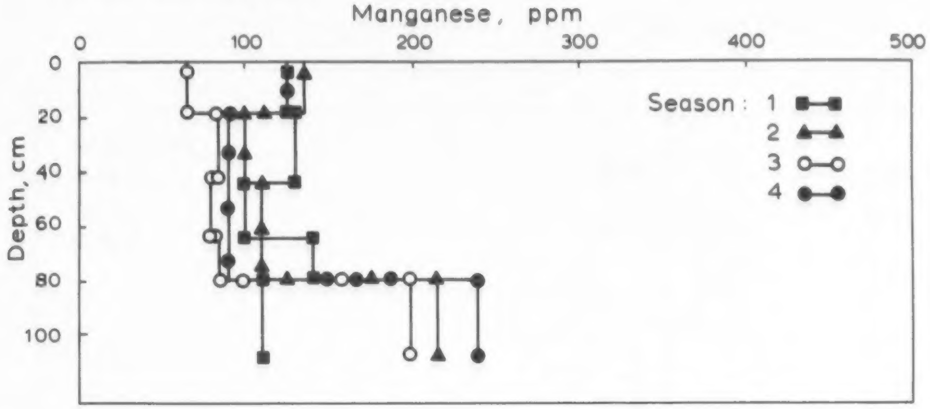
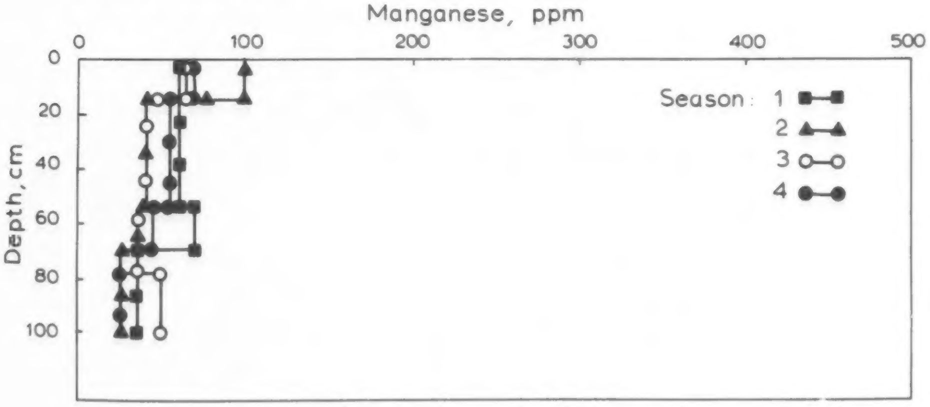


FIG. 8 - KLIDI



Figures 7 and 8. Depth distribution of EDTA extractable manganese as affected by the time of sampling (season 1 = sampling on Sept. 7, 1974; season 2 = sampling on Dec. 18, 1974; season 3 = sampling on Feb. 12, 1975; season 4 = sampling on June 6, 1975).

FIG.9-LANTZA

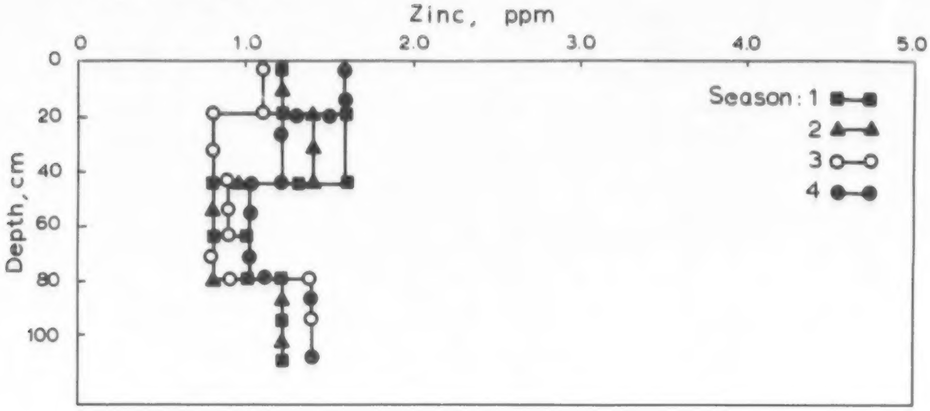
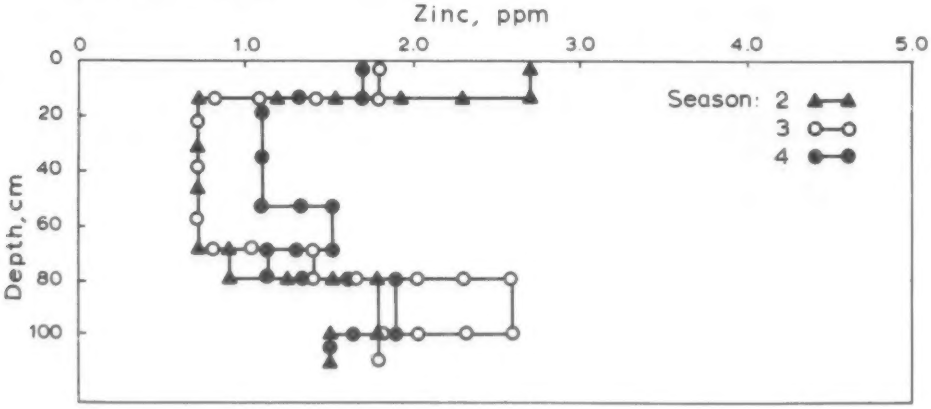


FIG.10-KLIDI



Figures 9 and 10. Depth distribution of EDTA extractable zinc affected by the time of sampling (season 1 = sampling on Sept. 7, 1974; season 2 = sampling on Dec. 18, 1974; season 3 = sampling on Feb. 12, 1975; season 4 = sampling on June 6, 1975).

Data regarding EDTA extractable iron levels, depth distribution, and seasonal variability are presented in Figures 11 and 12. The levels of extractable iron are higher in Lantza for the top 70 cm. Between 70 and 100 cm, however, there is a layer in the profile of Klidi, the EDTA extractable iron of which is quite high. The high extractable iron content of this layer is probably caused by the high organic matter content of of the layer and also the high water table. As to the value of these data it is generally accepted that plant chlorosis bears no general relation to total iron in the soils (Walliham, 1973) and no reliable index

FIG.11-LANTZA

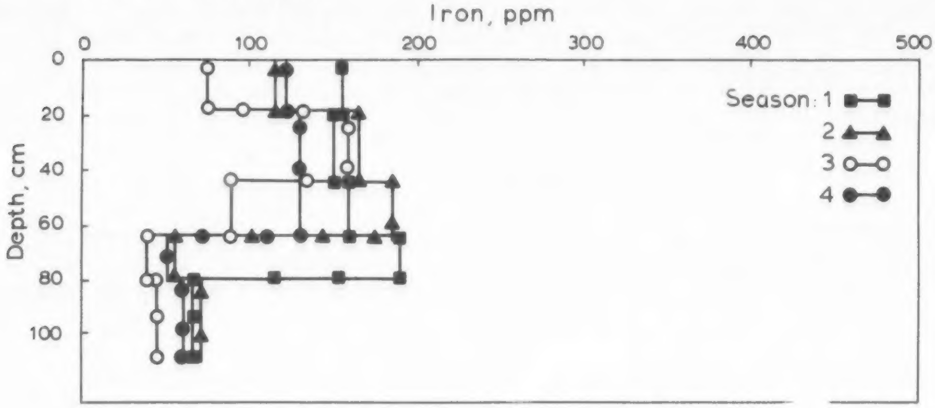
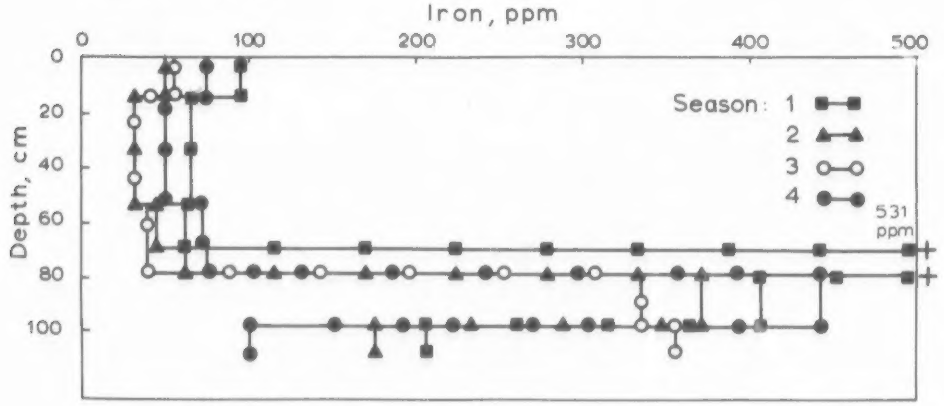


FIG.12-KLIDI



Figures 11 and 12. Depth distribution of EDTA extractable iron as affected by the time of sampling (season 1 = sampling on Sept. 7, 1974; season 2 = sampling on Dec. 18, 1974; season 3 = sampling on Feb. 12, 1975; season 4 = sampling on June 6, 1975).

on this matter is available. However, the amounts of iron extracted with chelating agent is correlated with the amounts obtained from the same soils by various plants (Brown and Holmes, 1956). It seems, thus, that the above data may give some idea as to the level of iron in these soils with respect to plant needs. If the plants require concentrations of the level of 100 ppm in their dry matter, then the above data possibly indicate satisfactory iron level for both profiles. With respect to seasonal variability there is some evidence of leaching during the rainy period, especially in the profile of Klidi.

In conclusion the above data give information concerning the level of B, Cu, Mn, Zn, and Fe in the studied profiles and indicate that during the rainy period there is probably some leaching of micronutrients together with the leaching of the salts. This implies that considerable amounts of micronutrients will be probably leached out of these soils during reclamation.

SUMMARY

In two salt affected areas of northern Greece (Lanta and Klidi near Thessaloniki) the distribution and seasonal variability of B, Cu, Mn, Zn, and Fe, along with the distribution and variability of salts, are presented.

The levels of boron are high in the soils of both areas and probably toxic to various plant species depending upon their relative tolerance to this element. Copper and iron are probably present in normal levels while the levels of manganese and zinc are probably low for the soils of both areas.

Regarding seasonal variability, there is evidence of leaching for boron, copper, zinc, and iron and also for salts during the rainy period, while the data for manganese are rather inconclusive.

It is concluded that considerable amounts of micronutrients will probably be leached out of these soils during reclamation.

LITERATURE CITED

Apostolakis, C.G., and Catherine E. Douka. 1970. Distribution of macro- and micronutrients in soil profiles developed on lithosequences and under biosequences in Northern Greece. Soil Sci. Soc. Am. Proc. 34: 290-296.

Bingham, F.T. 1973. Boron in cultivated soils and irrigation waters. Advances in Chem. Series. No. 123: 130-138.

Bower, C.A., R.F. Reitemeier, and M. Fireman. 1952. Exchangeable cation analysis of saline and alkaline soils. Soil Sci. 73: 251-261.

Bradford, G. R., R. J. Arkley, P. F. Pratt, and F. L. Bair. 1967. Total content of nine mineral elements in fifty selected benchmark soil profiles of California. Hilgardia Vol. 38, No. 14:541-556.

Brown, J. C., and R. S. Holmes. 1956. Iron supply and interacting factors related to lime induced chlorosis. Soil Sci. 82:507-519.

Callicoat, D. L., and J. D. Wolszon. 1959. Carminic acid procedure for determination of boron. Anal. Chem. 31:1434-1437.

Chapman, H. D. 1973. Zinc. In H. D. Chapman, ed., "Diagnostic Criteria for Plants and Soils". Quality Printing Co., Inc., Abilene, Texas. pp. 484-499.

Hammes, J. K. and K. C. Berger. 1960. Manganese deficiency in oats and correlation of plant manganese with various soils tests. Soil Sci. 90:239-244.

Hassan, N.A.K., J. V. Drew, D. Knudsen, and R. A. Olson. 1970A. Influence of soil salinity on production of dry matter and uptake and distribution of nutrients in barley and corn: I. Barley (Hordeum vulgare L). Agron. J. 62:43-45.

Hassan, N.A.K., J. V. Drew, D. Knudsen, and R. A. Olson. 1970B. Influence of soil salinity on production of dry matter and uptake and distribution of nutrients in barley and corn: II. Corn (Zea mays L.). Agron. J. 62:46-48.

Henriksen, A., and H. L. Jensen. 1958. Chemical and microbiological determination of copper in soil. Acta Agric. Skand. 8:441-469.

Labanauskas, C. 1973. Manganese. In H. D. Chapman, ed., "Diagnostic Criteria for Plants and Soils". Quality Printing Co., Inc., Abilene, Texas. pp. 264-285.

Maas, E. V., Gen Ogata, and M. J. Garber. 1972. Influence of salinity on Fe, Mn, and Zn uptake by plants. Agron. J. 64:793-795.

Mitchell, R. L. 1964. Trace elements in soils. "Chemistry of the Soil". F.E. Bear. Ed. Reinhold Publishing Co., New York. pp. 320-368.

Pagel, H., and R. N. Prasad. 1971. Zum Gehalt an "Verfügharen" microelementen in einigen Böden der Republik Zypern. Topizchen and Subtropischen Landwirtschaft 9, heft 2:147-158.

Reuther, W., and C. K. Labanauskas. 1973. Copper. In H. D. Chapman, ed., "Diagnostic Criteria for Plant and Soils". Quality Printing Co., Inc., Abilene, Texas. pp. 264-285.

Ure, A.M., and M. L. Berrow. 1970. Analysis of EDTA extracts of soils for copper, zinc, and manganese by atomic absorption spectrophotometry with a mechanically separated flame. Anal. Chem. Acta 52:247-257.

Viro, P. J. 1955. Use of Ethylenediaminetetraacetic acid in soil analysis: I. Experimental. Soil Sci. 79:459-465.

Walliham, E. F. 1973. Iron. In H. D. Chapman, ed., "Diagnostic criteria for plants and soils". Quality Printing Co., Inc. Abilene, Texas. pp.203-212.

CROP SALT TOLERANCE: EVALUATION OF EXISTING DATA

E. V. Maas and G. J. Hoffman [1]

INTRODUCTION

Salinity is perhaps the most important problem affecting irrigation agriculture in the world. It has been estimated that salinity limits crop production on 4×10^7 ha, or one-third of the world's irrigated land. In addition, millions of hectares of potentially irrigable land could become saline if put into production. It is imperative, therefore, that we provide the best salt-tolerance data available for crop selection and management decisions in these areas.

The U.S. Salinity Laboratory has conducted considerable research on plant salt tolerance, and the data compiled (Bernstein, 1964b; and U.S. Salinity Laboratory Staff, 1954) have been cited and used throughout the world. Since then, additional data have been obtained and innumerable publications have appeared dealing with salt tolerance. To provide current assessment of the relative tolerance of agricultural crops, we recently completed an extensive review and evaluation of the past 30 years' literature (Maas and Hoffman, 1976). Those data are presented graphically in this paper so that the relative tolerance among crops can easily be seen. The criteria required to express salt tolerance and the factors that influence and limit the use of these data are briefly discussed.

SALT TOLERANCE CRITERIA

Salt tolerance of agricultural crops typically is expressed as the decrease in yield associated with a given level of soil salinity as compared with yield under non-saline conditions (Berg, 1950; Bernstein, 1964b; Bernstein, 1974; de Forges, 1970; and U.S. Salinity Laboratory Staff, 1954). Acquisition of reliable salt-tolerance data requires appropriate measures of both soil salinity and plant response so that reductions in crop yield can be correlated with increases in salinity.

The primary salinity factors influencing plant growth are the kind and concentration of salts present in the soil solution. The predominate soluble ions in saline soils and waters are sodium, calcium, magnesium, bicarbonate, chloride, and sulfate. Except where ratios of these ions are extreme, most plants respond to salinity as a function of the total salt concentration or osmotic potential of soil water without regard to the salt species present (Bernstein, 1961). Nevertheless, some herbaceous plants and most woody species are susceptible to specific ion toxicities. For example, many fruit and berry crops are susceptible to chloride and sodium injury. Boron, an essential element for plant growth, is often found in saline soils at concentrations toxic to many plants. The maximum permissible levels of chloride, sodium, and boron in soil saturation extracts for some crops have been published (Bernstein, 1974). Occasionally, salinity induces nutritional imbalances or deficiencies that cause decreased growth and plant injury not attributable to osmotic effects alone (Bernstein, 1964a; and Bernstein and Hayward, 1958). Sulfate-induced calcium deficiency is one common example. Obviously, the relationship between total soluble salts in the root medium and crop yield must be corrected for these special cases.

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[1] U.S. Salinity Laboratory, Riverside, California.

Salt concentration in soils usually is determined by measuring the electrical conductivity of a soil saturation extract (EC_e) obtained from the active root zone (U.S. Salinity Laboratory Staff, 1954). The electrical conductivity of a solution is directly proportional to its concentration of soluble salts and, within limits, EC_e can be related to the EC of the soil water. For many soils, the soluble-salt concentration of the soil solution at field capacity is about twice that at saturation. Although EC_e can be routinely and reproducibly determined in the laboratory, in situ measurements of soil water salinity obviously are preferable. These measurements are now possible by using either salinity sensors (Oster and Ingvalson, 1967; and Oster and Willardson, 1971) or the four-electrode resistance probe (Rhoades and Ingvalson, 1971; and Rhoades, 1975).

Since salt distribution in the soil usually varies in both space and time, it is also important to know when and where to take salinity measurements. Except under irrigation with high-leaching fractions, salinity profiles are usually highly nonuniform, with concentrations ranging from about that of the irrigation water near the soil surface to many times higher at the bottom of the root zone. As a result of evapotranspiration and drainage, the salt concentration also changes with time between irrigations; consequently, irrigation frequency influences the magnitude of these changes.

Most salt-tolerance data were obtained where salinity was maintained essentially uniform throughout the root zone by irrigating soil plots or sand cultures with saline waters and high-leaching fractions. These conditions minimize the ambiguity encountered when interpreting results obtained from nonuniform salinity profiles. However, applying these data to field conditions where the distribution of salt is neither uniform in depth nor constant with time is difficult and requires knowledge of how plants respond to varying salinity. Assuming that plants respond primarily to the soil water salinity in that part of the root zone with the highest total water potential, then time-integrated salinity measured in the zone of maximum water uptake should correlate best with crop response. Under high-frequency irrigation, this zone corresponds primarily to the upper part of the root zone where soil salinity is influenced mostly by the salinity of the irrigation water (Bernstein and Francois, 1973). With infrequent irrigation, the zone of maximum water uptake becomes larger as the plant is forced to extract increasingly saline water from increasingly greater depths.

The only agronomically important plant criterion for establishing salt tolerance is the commercial yield of the crop. Vegetative growth, although often used, is not always a reliable guide for predicting fruit or seed production. Grain yields of rice (Pearson, 1959) and corn (Kaddah and Ghowail, 1964) may be greatly reduced without appreciably affecting straw yield. With some other crops, e.g., barley, wheat, cotton, and some tolerant grasses, seed or fiber production is decreased much less than vegetative growth (Ayers, Brown, and Wadleigh, 1952; and unpublished USSL data). For root crops, storage-root yields may be decreased much more than that of tops or fibrous roots (Hoffman and Rawlins, 1971; and Lunin, Gallatin, and Batchelder, 1963).

FACTORS INFLUENCING SALT TOLERANCE

Salt tolerance is a relative value based upon the climatic and cultural conditions under which the crop was grown. Salt tolerance lists published by the U.S. Salinity Laboratory (Bernstein, 1964b; Bernstein, 1974; and U.S. Salinity Laboratory Staff , 1954) represent relative tolerance when crops are grown under conditions simulating cultural and management practices recommended for commercial production in the southwestern United States. Absolute tolerances that reflect predictable inherent physiological responses by plants cannot be determined because many interactions among plant, soil, water, and environmental factors influence the plant's ability to tolerate salt.

Plant sensitivity to salinity often varies from one growth stage to the next (Maas and Hoffman, 1976). For example, barley, corn, rice, and wheat are more sensitive during emergence and early seedling growth than during germination and later stages of growth and grain development. In contrast, sugarbeet and safflower are most sensitive during germination. To avoid problems at sensitive stages of growth, one must know the salt tolerance at these specific stages for some crops and use appropriate management practices to reduce salinity. Although salt tolerance is usually reported as single value for a crop, several examples of varietal differences are now known (Maas and Hoffman, 1976). Interestingly, these crops (e.g., bermudagrass, bromegrass, bentgrass, barley, rice, wheat, soybean, birdsfoot trefoil, and berseem clover) belong to either the Gramineae or Leguminosae families. Perhaps as crops are developed from an increasingly diverse genetic base, even more variability will be found. Rootstocks must be considered in evaluating salt-tolerance differences among tree and vine crops. Salt tolerance of avocado, citrus, grapes, and many stone-fruit trees is related to the ability of rootstocks to exclude chloride.

Soil fertility interacts with salinity to affect the apparent tolerance of many crops. These interactions and how they affect interpretations of salt tolerance data have been discussed by Bernstein, Francois, and Clark (1974). Crops generally seem more salt tolerant when grown with poor rather than with adequate fertility, but only because yields are depressed more by inadequate nutrition under non-saline than under saline conditions. Although fertilization increases yields on infertile saline soils, it usually has no effect on relative salt tolerance because it increases yields proportionately more on comparable non-saline soils. Unless salinity causes specific nutritional problems, fertilization in excess of that required for non-saline soil usually has little beneficial effect and may, in fact, aggravate salt injury (Bernstein, Francois, and Clark, 1974). Other soil factors that may influence crop salt tolerance include soil matric potential, leaching fraction, poor soil aeration, and a shallow water table.

Climatic conditions often influence plant response to salinity. Many crops appear less salt tolerant when grown in a hot, dry climate than in a cool, humid one (Magistad, Ayers, Wadleigh, and Gauch, 1943). Hoffman and co-workers (Hoffman and Rawlins, 1971; and Hoffman, Rawlins, Garber, and Cullen, 1971) found that high atmospheric humidity tended to increase salt tolereance, especially that of salt sensitive crops. Controlled-environment studies indicate that air pollution may increase the apparent salt tolerance of many crops. For example, alfalfa grown at ozone concentrations often prevalent in several agricultural areas, yields were highest at moderate salinity levels that normally reduce growth (Hoffman, Maas, and Rawlins, 1975). Because some crops are affected more by air pollutants when grown under non-saline than under saline conditions, they may seem more salt tolerant in air-polluted areas.

SALT TOLERANCE EVALUATIONS

The most difficult task in evaluating crop salt tolerance data is accounting for the many factors that may influence the plant's response to salinity. A review of the literature reveals that many experimental procedures have been used for determining salt tolerance. Experiments have been conducted in soil, sand, and water cultures; in field, small plots, greenhouse, and growth chambers; and under nearly every conceivable environmental condition. Salination methods have differed, as have ways of measuring and reporting salinity levels in the root medium. Likewise, plant response to salinity has been measured in several ways and at various stages of growth and development. In many experiments, important variables were either not measured or reported, or were uncontrolled.

Notwithstanding the difficulties in evaluating and normalizing the extensive data published worldwide, we have compiled and reviewed all available salt tolerance data from the past 30 years to present our best assessment of the relative salt tolerance of agricultural crops (Maas and Hoffman, 1976). In general, only those data correlating crop yield to the total soluble salts in the root medium were considered. Sodic soil conditions, specific ion toxicities, and nutritional effects were not evaluated. Unfortunately, vegetative growth had to be used for some tree and vine crops because of the lack of yield data. Experiments without adequate control of the factors influencing salt tolerance and papers that failed to mention these factors were not considered in the salt tolerance evaluations. For ease in interpretation, all salinity values were converted to EC_e and all yield data were converted to a relative basis, with the yield of the control treatment assigned a value of 100.

The salt tolerance data for 61 crops are presented in Figures 1-8. In general, crop yields were not decreased significantly until a threshold salinity level was exceeded, and then yields decreased approximately linearly as salinity increased beyond the threshold. The few exceptions to this were of minimal concern because deviations from linearity occurred in the lower part of the curve where yields were commercially unacceptable. The salt-tolerance curve for each crop was obtained by calculating a linear regression equation for the yield data beyond the threshold from each individual experiment. When more than one experiment was considered for determining the salt tolerance of a crop, the slope and intercept values for the various experiments were averaged. In some cases, inclusion or exclusion of data required subjective judgment. Because of the limited salinity range tested in some studies, data from some experiments could be used only to establish threshold salinities and those from others only to determine slope.

Relative yield (Y) at any given soil salinity (EC_e) can be calculated by the equation

$$Y = \frac{100\ (EC_0 - EC_e)}{EC_0 - EC_{100}}$$

where EC_{100} is the salinity threshold value (EC_e where $Y = 100$) and EC_0 the salinity at zero yield (EC_e where $Y = 0$). The values for EC_{100} and EC_0 for a given crop can be taken from the appropriate figure. Using alfalfa as an example, $EC_{100} = 2$ mmho/cm and $EC_0 = 15.7$ mmho/cm from Figure 3; therefore, at a soil salinity of 5.4 mmho/cm, the relative yield, $Y = 100(15.7 - 5.4)/(15.7 - 2.0) = 75\%$.

A qualitative salt tolerance rating for each crop is also indicated by the shaded areas in the figures. Four divisions were selected to correspond with commonly used terminology ranging from sensitive to tolerant (Fig. 1). The division boundaries for these qualitative ratings approximate the slopes of the linear curves that represent most of the crops reported. With few exceptions the linear salt tolerance curve for each crop remained within one division. Where the salt tolerance curve crosses division boundaries, the crop is rated based on its tolerance at salinity levels where yields are commercially acceptable. Because of insufficient data to determine curves for some crops, only qualitative salt tolerence ratings could be assigned and these are listed in Table 1.

Table 1: Qualitative salt tolerance rating of crops lacking sufficient data for quantitative rating.

Crop Salt Tolerance Rating			
Sensitive	Moderately Sensitive	Moderately Tolerant	Tolerant
Apple	Bentgrass	Bromegrass	Wildrye, Altai
Avocado	Millet, Foxtail	Canarygrass, seed	Wildrye, Russian
Lemon	Rhodesgrass	Olive	
Okra	Timothy	Safflower	
Raspberry		Sorghum	
		Wheatgrass, slender	

The salt tolerance evaluations presented here agree remarkably well with data published from this Laboratory (Bernstein, 1964b; and Bernstein, 1974) even though new and additional experimental data were used for many crops. Only the tolerance of garden beet and bermudagrass changed significantly and both seem less tolerant than previously reported. The threshold salinities of corn, grape, and spinach dropped slightly as compared with extrapolated values from Bernstein's evaluations (Bernstein, 1974), whereas threshold salinities of cotton, soybean, and wheat increased about 1 mmho/cm. Several new crops were added to the list but quantitative evaluations of a few others were not included because the data were equivocal.

In summary, we again emphasize that these data do not represent absolute salt tolerances independent of other factors. Instead, they furnish a guide to relative tolerances among various crops. Whereas absolute tolerance vary with climate, cultural practices, and other variables, relative tolerance should apply to most conditions.

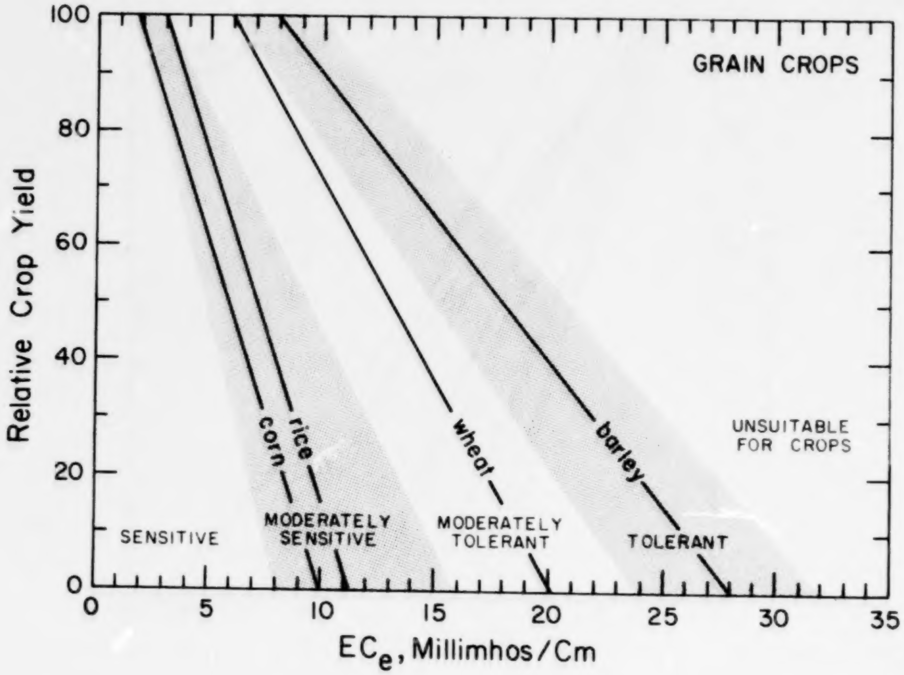

Figure 1: Salt Tolerance of Grain Crops

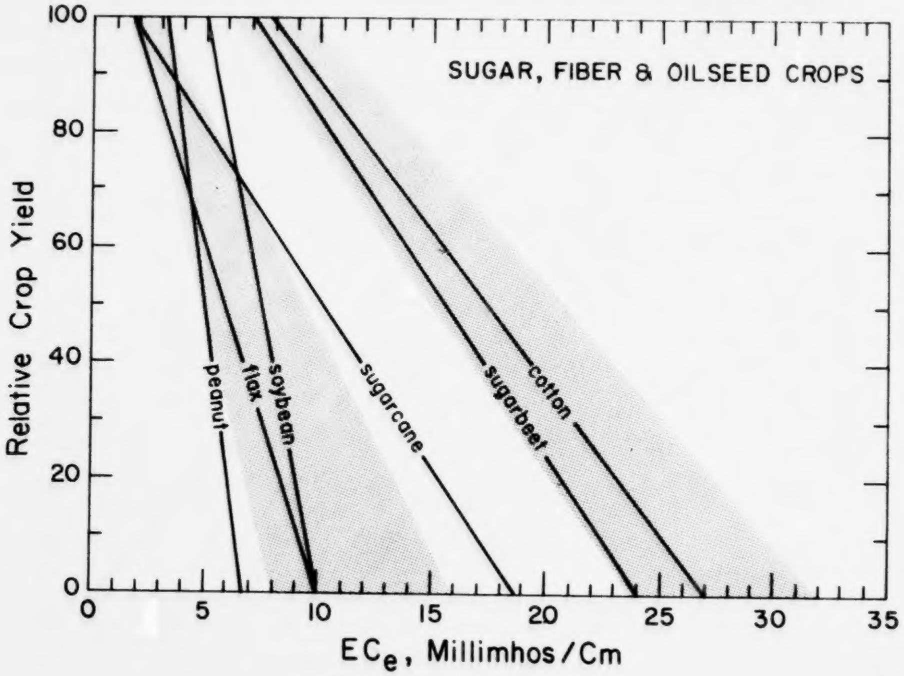

Figure 2: Salt Tolerance of Sugar, Fiber and Oilseed Crops

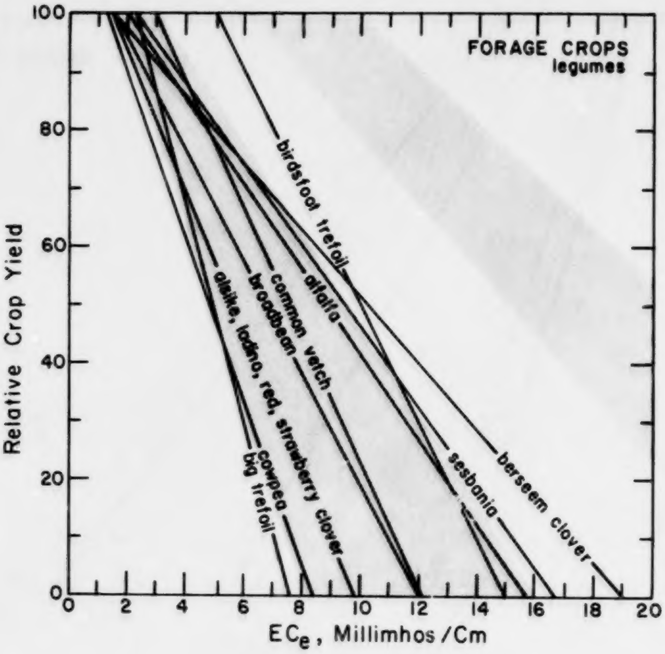

Figure 3: Salt Tolerance of Forage Crops - Legumes

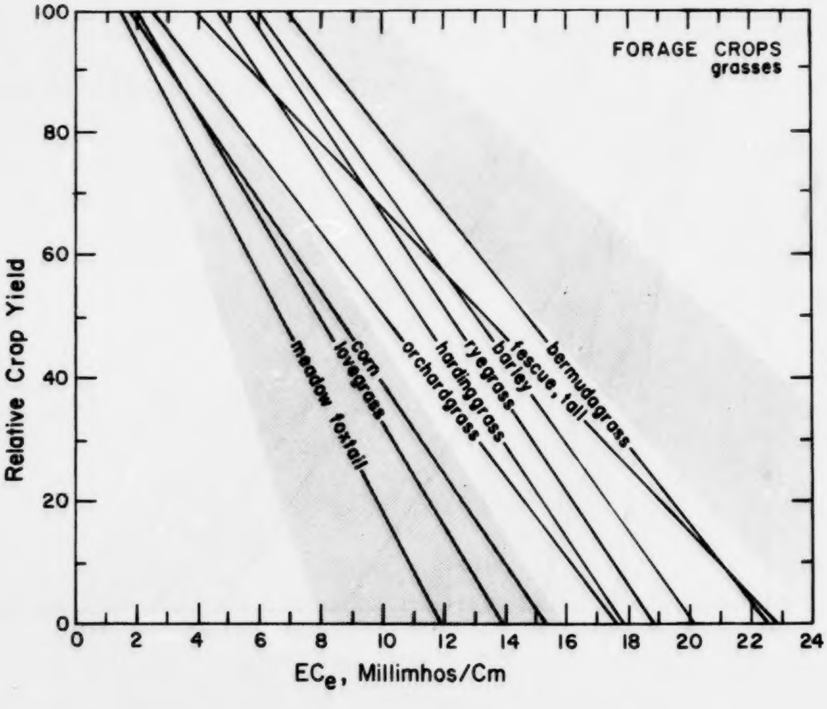

Figure 4: Salt Tolerance of Forage Crops - Grasses

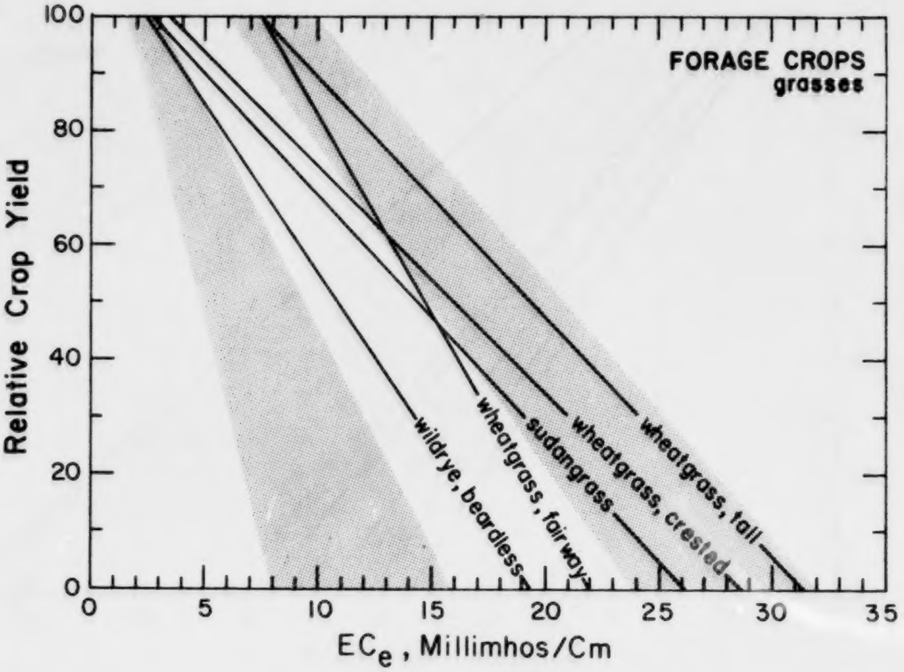

Figure 5: Salt Tolerance of Forage Crops - Grasses

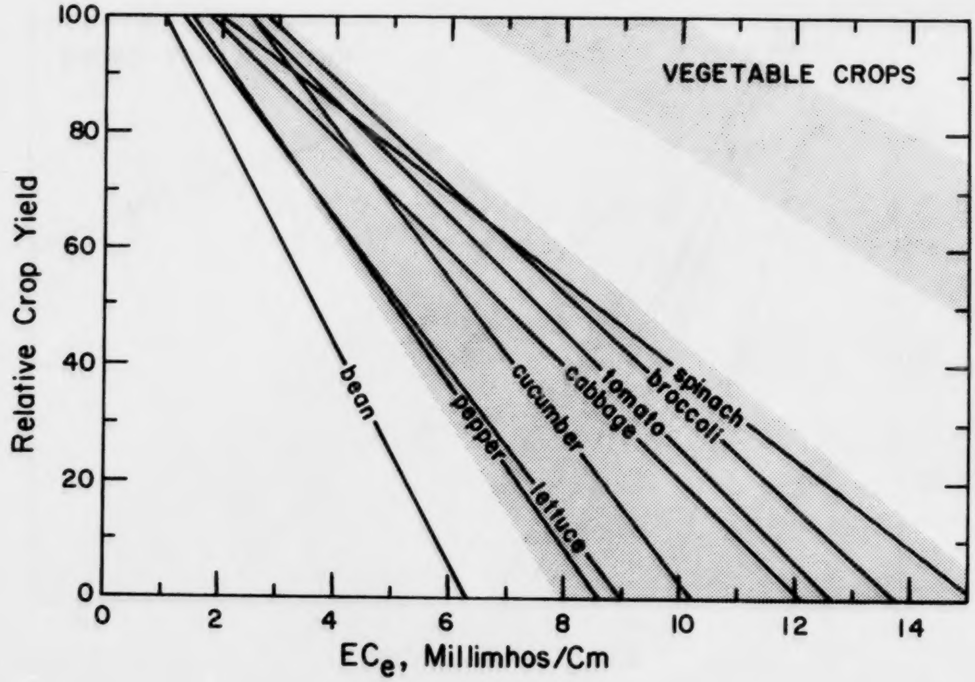

Figure 6: Salt Tolerance of Vegetable Crops

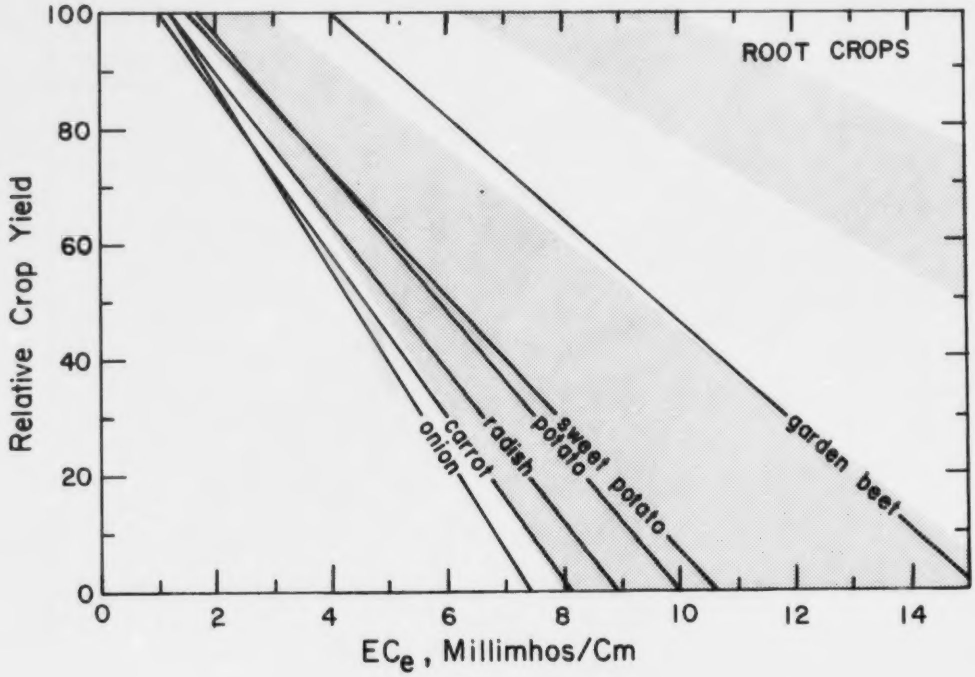

Figure 7: Salt Tolerance of Root Crops

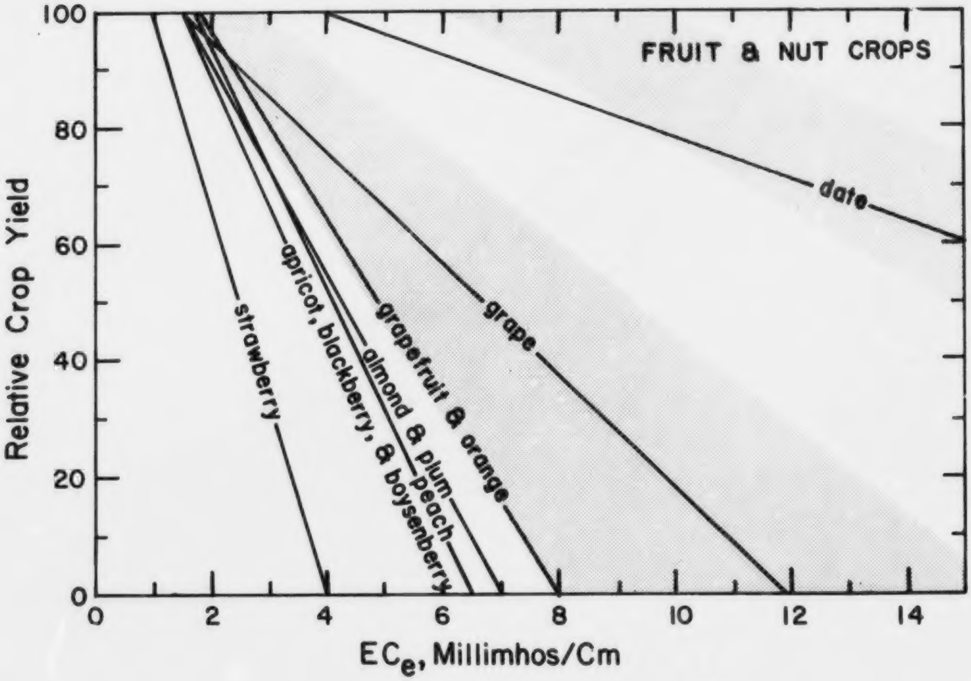

Figure 8: Salt Tolerance of Fruit and Nut Crops

REFERENCES

Ayers, A. D., J. W. Brown, and C. H. Wadleigh. 1952. Salt tolerance of barley and wheat in soil plots receiving several salinization regimes. Agron. J. 44:307-310.

Berg, C. V. D. 1950. The influence of salt in the soil on the yield of agricultural crops. Fourth Intl. Cong. Soil Sci. Trans. 1:411-413.

Bernstein, L. 1961. Osmotic adjustment of plants to saline media. I. Steady state. Am. J. Bot. 48:909-918.

Bernstein, L. 1964a. Effects of salinity on mineral composition and growth of plants. Proc. 4th Intl. Colloquium Plant Analysis and Fert. Problems (Brussels) 4:25-45.

Bernstein, L. 1964b. Salt tolerance of plants. U.S. Dept. Agr. Inf. Bull. 283. 23 pp.

Bernstein, L. 1974. Crop growth and salinity. In: Jan van Schilfgaarde (ed.), Drainage for agriculture. Agronomy 17:39-54. Am. Soc. Agron., Madison, Wisconsin.

Bernstein, L. and L. E. Francois. 1973. Leaching requirement studies; sensitivity of alfalfa to salinity of irrigation and drainage waters. Soil Sci. Soc. Am. Proc. 37:931-943.

Bernstein, L., L. E. Francois, and R. A. Clark. 1974. Interactive effects of salinity and fertility on yields of grains and vegetables. Agron. J. 66:412-421.

Bernstein, L. and H. E. Hayward. 1958. Physiology of salt tolerance. Annu. Rev. Plant Physiol. 9:25-46.

de Forges, J. M. 1970. Research on the utilization of saline water for irrigation in Tunisia. Nature and Resources VI:2-6.

Hoffman, G. J., E. V. Maas, and S. L. Rawlins. 1975. Salinity-ozone interactive effects on alfalfa yield and water relations. J. Environ. Qual. 4:326-331.

Hoffman, G. J. and S. L. Rawlins. 1971. Growth and water potential of root crops as influenced by salinity and relative humidity. Agron. J. 63:877-880.

Hoffman, G. J., S. L. Rawlins, M. J. Garber, and E. M. Cullen. 1971. Water relations and growth of cotton as influenced by salinity and relative humidity. Agron. J. 63:822-826.

Kaddah, M. T. and S. I. Ghowail. 1964. Salinity effects on the growth of corn at different stages of development. Agron. J. 56:214-217.

Lunin, J., M. H. Gallatin, and A. R. Batchelder. 1963. Saline irrigation of several vegetable crops at various growth stages. I. Effect on yields. Agron. J. 55:107-110.

Maas, E. V. and G. J. Hoffman. 1976. Crop salt tolerance - current assessment. (Submitted to J. Irrig. and Drainage, Div. Am. Soc. Civil Eng.).

Magistad, O. C., A. D. Ayers, C. H. Wadleigh, and H. G. Gauch. 1943. Effect of salt concentration, kind of salt, and climate on plant growth in sand cultures. Plant Physiol. 18:151-166.

Oster, J. D., and R. D. Ingvalson.. 1967. In situ measurement of soil salinity with a sensor. Soil Sci. Soc. Am. Proc. 31:572-574.

Oster, J. D., and L. S Willardson. 1971. Reliability of salinity sensors for the management of soil salinity. Agron. J. 63:695-698.

Pearson, G. A. 1959. Factors influencing salinity of submerged soils and growth of Caloro rice. Soil Sci. 87:198-206.

Rhoades, J. D., and R. D. Ingvalson. 1971. Determining salinity in field soils with soil resistance measurements. Soil Sci. Soc. Am. Proc. 35:54-60.

Rhoades, J. D. 1975. Measuring, mapping and monitoring field salinity and water table depths with soil resistance measurements. Proc., Expert Consultation on Prognosis of Salinity and Alkalinity, Rome, Italy, June 1975. (In press).

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S. Dept. Agr. Handbook 60. 160 pp.

SOIL SALINITY AND PLANT NUTRITIONAL STATUS

Arnold Finck 1/

INTRODUCTION

Salinity imposes a double stress on non-halophytic plants, i.e., water deficiency at higher salt contents and nutritional disturbances at low or medium degrees of salinity. Since plants require a balanced nutrition with nutrient contents in the optimum range and other elements below a harmful level, the concept of plant analysis interpretation is applied in order to explain crop growth differences on partly salt damaged soils in southern Italy (Schleiff and Finck, 1976).

Summarized results of this investigation present the base for a discussion of some changes of the nutritional status (mainly cations) under salinity influences. The final object is a system of limiting values both for deficiency and toxicity adapted to saline conditions for diagnostic purpose and conclusions for the improvement of nutritional disturbances by special fertilization.

EXPERIMENT

Plant samples were taken from fields with growth differences due to the saline soil. The samples were from patches of good, medium, and poor growth crops, mainly wheat plants being, respectively, about 65, 35 and 25 cm high during the age of shooting. The plant analysis data mentioned refer to contents in dry matter of all aboveground parts, expressed as %o (parts per thousand).

The investigated area of the Sibari plain in southern Italy consists of coastal alluvial soils of varying, mostly medium, texture. They are variable in the degree of salinty and in the area effected, with Na in the exchange complex being mostly below 5%. The soluble salts are high in Na and partially high in Mg (Cl and SO_4 being present in about equal portions). Soluble salts are determined in the 1:5 extract, exchangeable cations by extraction with 0.025 N $CaCl_2$.

Since the interpretation is based on supply ranges and critical levels, the following nomenclature is suggested: **(Fig. 1.)**

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<table>
<tr><th></th><th>A</th><th>B</th><th>C</th><th>D</th><th>E</th><th>F</th></tr>
<tr><td>essential elements</td><td colspan="2">acute latent
deficiency</td><td rowspan="2">optimum supply</td><td rowspan="2">luxury consumption</td><td rowspan="3">latent toxicity</td><td rowspan="3">acute toxicity</td></tr>
<tr><td>beneficial elements</td><td colspan="2">'deficiency'</td></tr>
<tr><td>useless or toxic elements</td><td colspan="4">harmless normal content</td></tr>
</table>

Fig. 1: Ranges of contents of elements in plants

RESULTS

The aim of this investigation is the detection of nutritional disturbances, e.g., surplus of total salts, Na, and Mg or deficiency of K, Ca, etc. disregarding for the time being other possible causes of yield depressions (water deficiency, oxygen deficiency due to structural deterioration, etc.).

Total Salts in Plants

Increasing salt contents of the soils resulted in poor growth of wheat, especially if the amounts exceeded 4-5%o, but the salt content of the plants (measured as the sum of cations) was hardly increased. Most samples of good or bad growth were in the range of 1-1.4 meq/g of cations in the dry matter.

Surplus of Na

As expected, the Na contents of wheat plants increased with water soluble Na in the soils. The result is poorer growth above a concentration of about 1.5%o Na (Fig. 2).

There exists, however, a great variation in plant content at similar Na levels in the soil. High and harmful Na contents are often found together with low K contents of plants, or, expressed differently, K contents above 30-35%o seem to keep the Na content below 3%o (Fig. 3). A surplus of Na, thus, seems to be a detrimental factor acting via Na toxicity or via induced K deficiency.

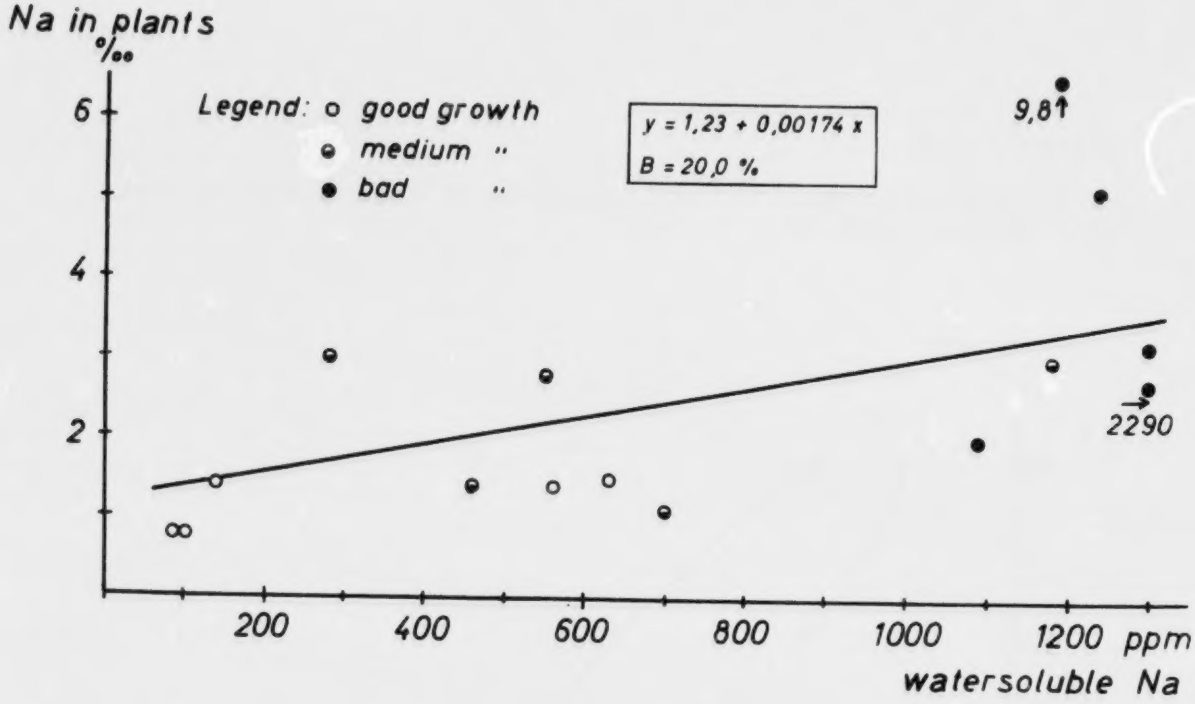

Fig. 2: Na contents of wheat plants in relation to water soluble Na of the soils.

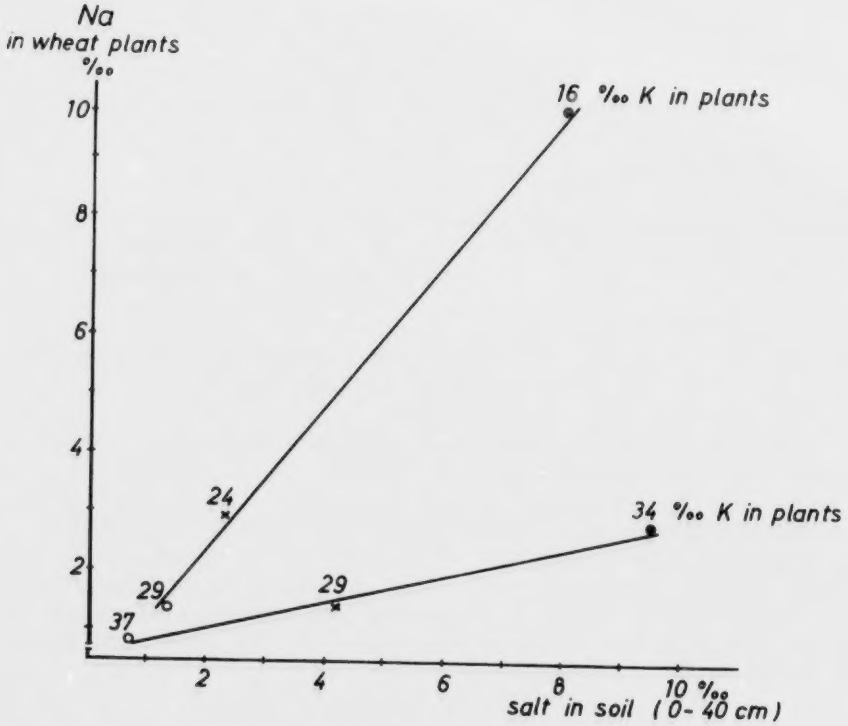

Fig. 3: Na content of wheat plants on saline fields influenced by K-supply (for explanation of growth differences see Fig. 2).

Deficiency of K

At medium salt content of the soil the growth of wheat is improved with better K supply (Fig. 4).

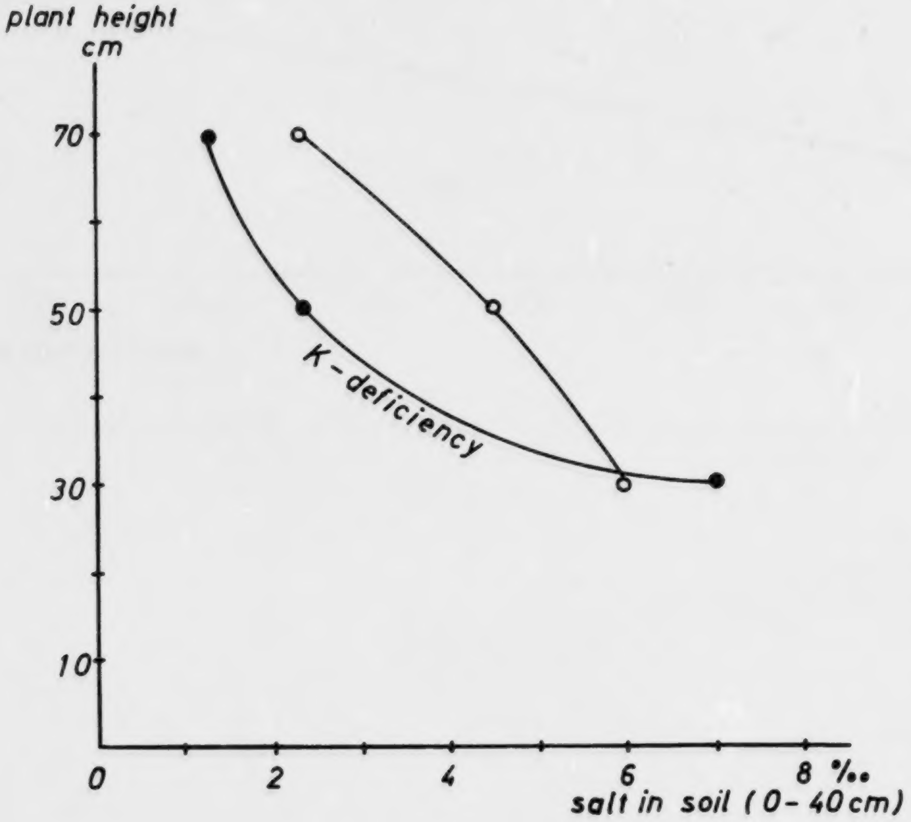

Fig. 4: Growth of wheat plants on saline soils depending on K supply (for explanation of growth differences see Fig. 2).

K deficiency is the result of an insufficient supply and/or of antagonistic exclusion due to high Na and Mg in soils. The contents of exchangeable K in soil are in the range of 30-90 ppm, the highest soil K value producing the lowest plant K concentration (16%o) in combination with the high Na content of 10%o. The poor growth observed in spite of a rather good K supply of 34%o (Fig. 3) seems to be due to a low Ca content (only 1.4%o). Fig. 5 shows how the limiting value of optimum K supply in plants is probably dependent on the concentration of Na present in plants.

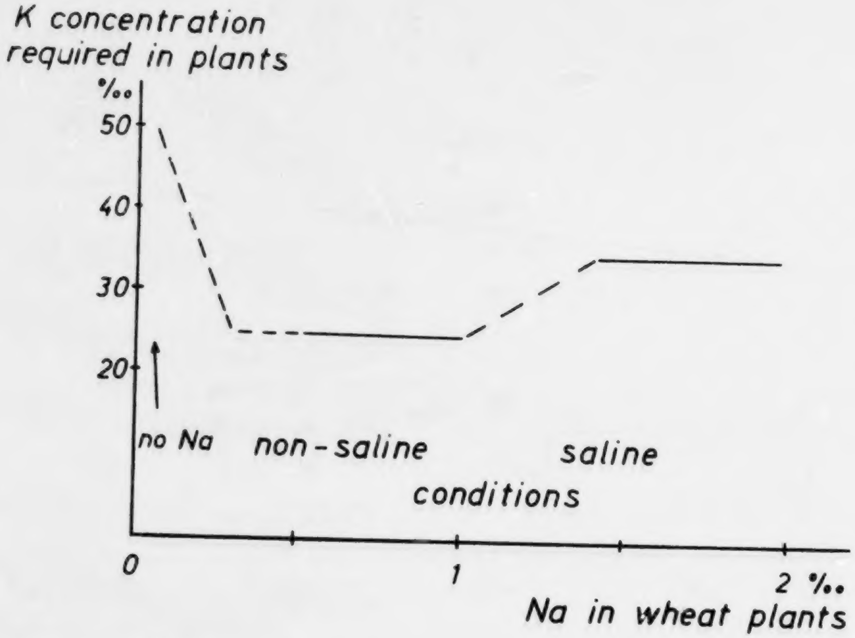

Fig. 5: Limiting value for optimum K supply depending on Na contents of wheat plants at beginning of shooting.

For wheat the following critical nutrient levels are suggested (Table 1).

Table 1: Critical Nutrient Levels for Optimum K Supply of Wheat

Stage of Growth	%o K in Plants on	
	Non-Saline Soils	Saline Soils
Beginning of Shooting	25	35
Appearance of Ears	20	30

Surplus or Deficiency of Mg

Since plants in pot experiments with increasing supply of exchangeable Mg up to 25 mc/100g took up high amounts of Mg (up to 9%o) and showed a yield decrease to 50%, it was assumed that a surplus of Mg might be another cause of growth reduction on soils rich in available (exchangeable) Mg. This is, however, not the case on the soils investigated with exchangeable Mg up to 9 mc/100g. On the contrary, the Mg contents were more in the range of optimum supply rather than within luxury consumption (Finck and Schleiff, 1972) (Fig. 6).

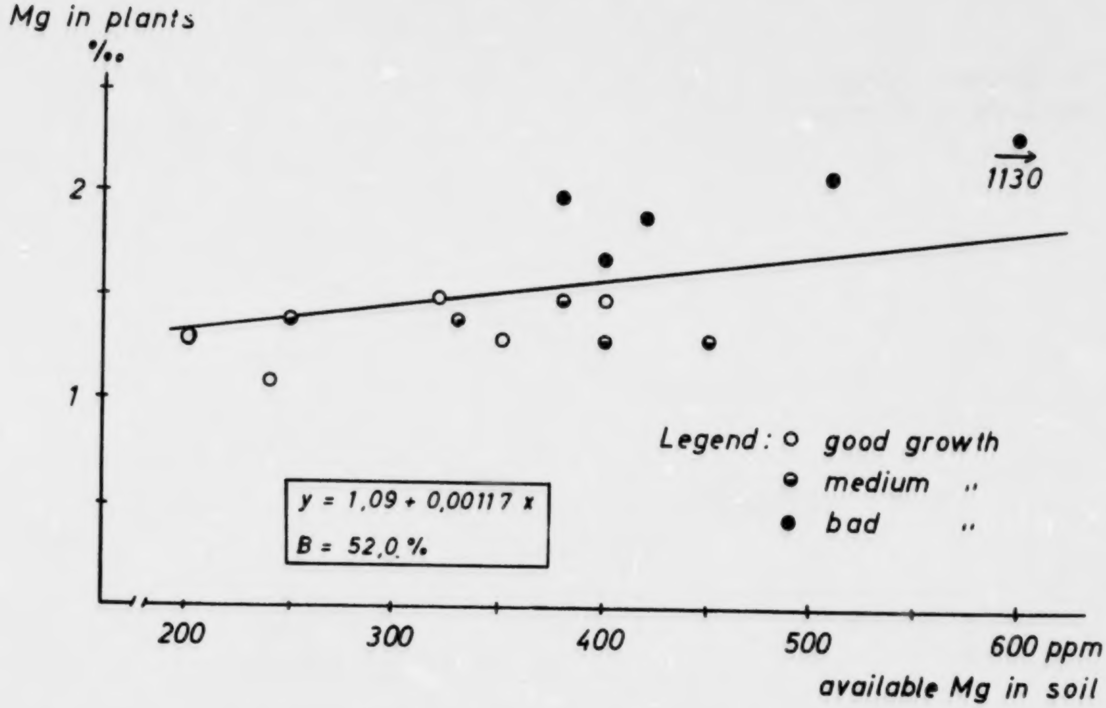

Fig. 6: Mg content of wheat plants in relation to available Mg.

A surplus of Mg in plants above 5-6%o can, therefore, be excluded as a possible cause of the growth reduction.

Since in non-saline soils about 8 mc/100g of exchangeable Mg is sufficient for optimum supply, the question must be raised whether (in spite of an abundant supply of soil Mg) a deficiency in plants may occur due to antagonistic effects. The range of optimum supply at the beginning of shooting starts at about 1.2-1.5%o Mg if the Mg/Ca ratio is greater than 0.3 (Wichmann, 1976). Thus on saline soils the limiting values will probably be even lower because of the higher Mg/Ca ratios, which are all above 0.5. The wheat plants investigated therefore do not seem to suffer from Mg deficiency, although generally in saline soils Mg deficiency has to be considered.

Deficiency of Ca

In calcareous soils the Ca supply is expected to be at least in the optimum range if not within luxury consumption. Although the Ca concentrations due to the greater immobility of Ca are not as good an indicator of the nutritional status as those of K, Na,or Mg, total Ca contents of about 3-5%o seem to be required. This can also be shown with wheat in pot experiments (Fig. 7).

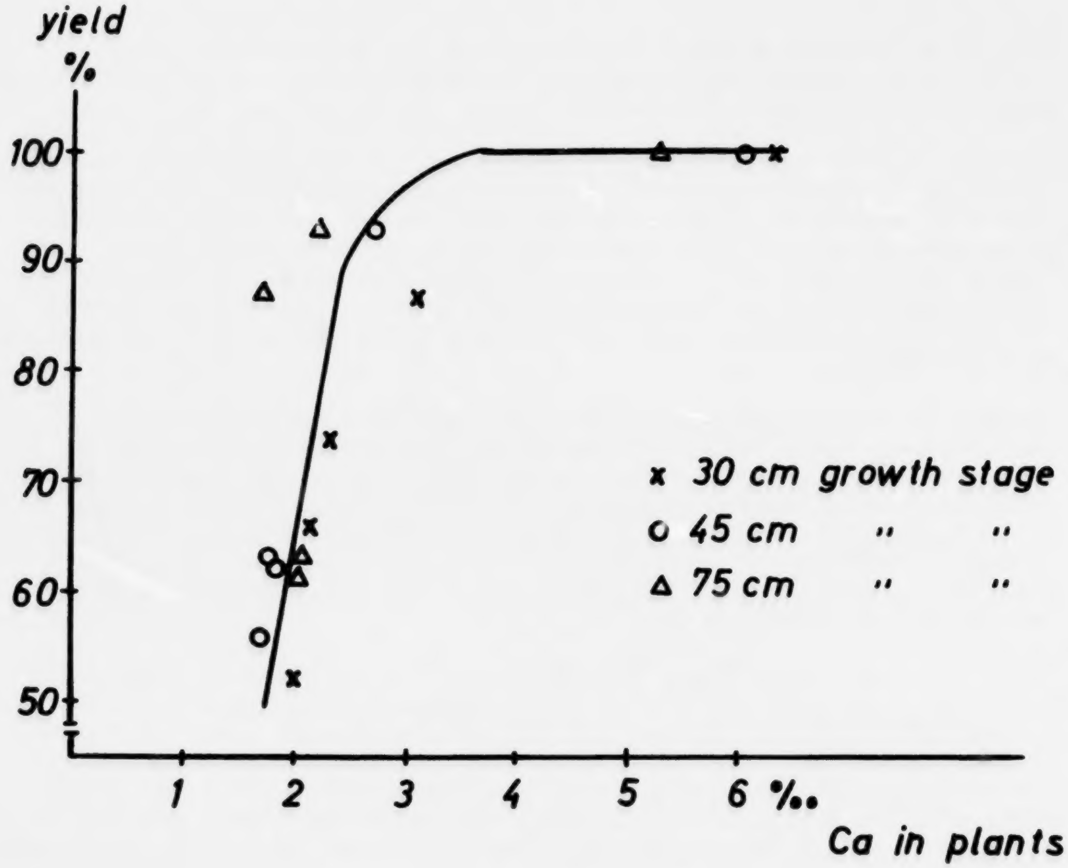

Fig. 7: Vegetative dry matter yield of wheat in water culture with increasing supply of Mg causing Ca deficiency.

Wheat plants on slightly acid soils in Germany contain normally more than 4%o Ca at the beginning of shooting. The Ca contents of wheat under the saline conditions investigated ranged from 2-3.2%o at good growth and down to 1.2-1.4%o in part of the samples from medium and poor growth. Low Ca contents are generally combined with high Na contents.

For whatever reason, it may be concluded that the Ca content of wheat in the Sibari area is rather low even in the plants of good growth, and sometimes is apparently in the deficiency range.

DISCUSSION

The influence of increasing salinity on plants has many aspects which have been discussed in the literature, e.g., the physiology of salt tolerance and injury (Bernstein and Hayward, 1958; Strogonov, 1964; Elgabaly, 1961; van den Berg, 1973; Oertli, 1976).

The intention of this paper, however, is to put more emphasis on the influence of salinity on the general nutritional situation in view of surplus or deficiency of nutrients.

As long as the water stress is tolerable (at low and medium salt contents) plants try to exclude unwanted ions as far as possible and to promote the uptake of nutrients. With increasing salt content the uptake of Na becomes more pronounced (two mechanisms have been described by Epstein and Hagen, 1952; Rains, 1972). This salt luxury consumption is essential for the compensation of an increasing outside osmotic pressure, but harmful for the nutritional situation, causing growth depressions due to surpluses and deficiencies.

In this "ecological approach", plant analysis data are interpreted according to supply ranges. For some nutrients, however, the limiting values generally obtained on non-saline soils (e.g., for wheat; Finck, 1976) have to be adapted to saline conditions. A modification of the present diagnostic system is therefore required. With increasing Na contents, higher K concentrations are necessary in plants. Due to a high Mg/Ca ratio, the Mg contents of plants can be lower than usual without indicating Mg deficiency.

In the southern Italy area investigated, increasing salinity resulted in a surplus of Na, but not in a surplus of Mg (Finck and Schleiff, 1972). Furthermore, a deficiency of K and Ca seems to play an important role in growth depressions. Similar effects have been observed or suspected already for K (Heimann, 1966) and for Ca (Chang and Dregne, 1955). The plant data of Ca can certainly be used only with precaution, and the analysis of only the youngest leaves would have been preferable (Loneragan and Snowball, 1969).

In general, plant analysis seems to be a useful supplementary diagnostic method, since soil analysis (although indicating the supply of available nutrients) fails to state the degree of utilization in the presence of antagonists.

The result of our investigations can be summarized by Fig. 8 showing that even at a certain salt content of the soil the growth depression can be offset with a balanced good nutrition.

The supply of trace elements under saline conditions has not yet been included in our studies. A disturbed balance of the major nutrient cations together with high soil pH is bound to influence the trace element composition of plants (Ravikovitch and Navrot, 1976). Besides the well-known excess of boron, the nutritional status of the cations (Fe, Mn, Zn, Cu) should be better investigated, especially the validity of the limiting values developed for non-saline soils.

Fertilization of soils with low or even medium salt content should, besides saving water (Kafkafi, 1973) serve also to:

1. supplement nutrients that are insufficient in soil;

2. supplement nutrients that, although abundant, are not taken up adequately due to antagonistic effects, e.g., K (Heimann, 1966) or Ca (Poonia and Bhumla, 1973); and

3. decrease the uptake of harmful surpluses, e.g., K against Na or nitrate and phosphate against chloride (Röber, 1969; Ravikovitch and Porath, 1967).

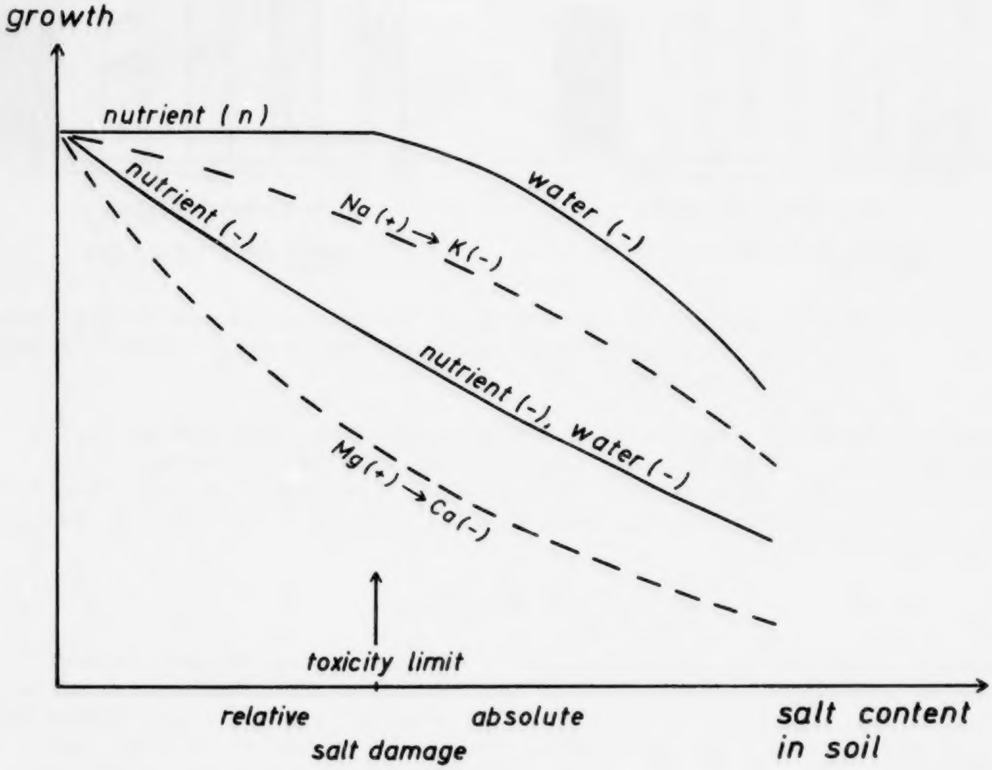
growth
nutrient (n)
water (-)
nutrient (-)
Na(+) → K(-)
nutrient (-), water (-)
Mg(+) → Ca(-)
toxicity limit
relative
absolute
salt damage
salt content in soil

Fig. 8: Salinity and plant growth (nutrient(n) means normal supply, nutrient(-) means deficiency, e.g., Na(+) surplus causing K(-) deficiency).

The following figure demonstrates schematically how a well adjusted fertilization could improve the nutritional status of plants and therefore also the yield (Fig. 9).

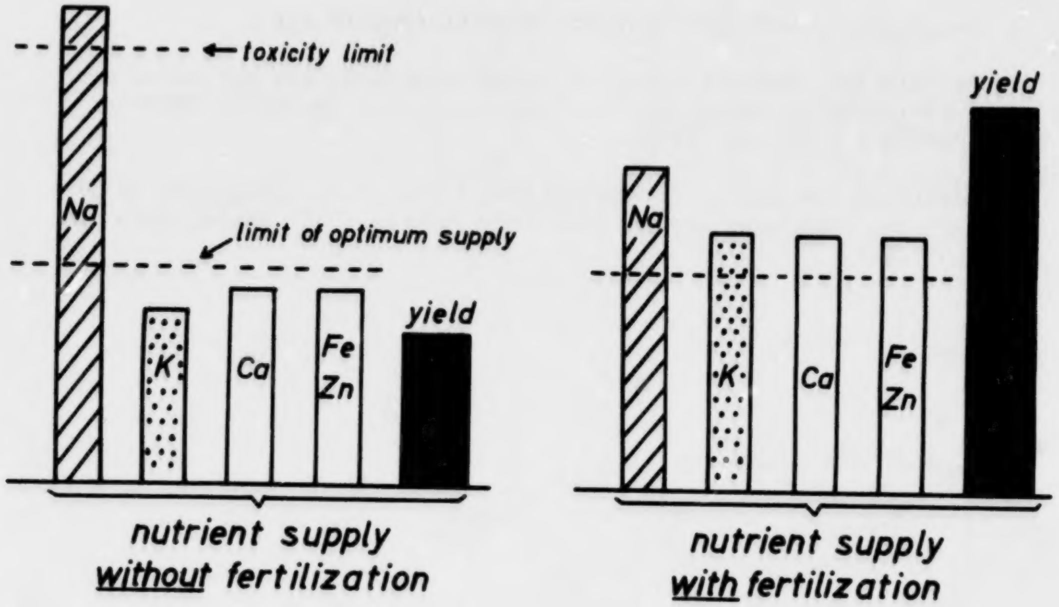

Fig. 9: Fertilization for correction of an unbalanced and insufficient nutrient supply of plants on saline soils (the columns indicating the plant contents).

Fertilization of saline soils should on the other hand add as little soluble salts as possible in order not to increase the water stress unnecessarily. High grade fertilizers are preferable or fertilizers with no unnecessary anions, such as KNO_3 instead of KCl or urea instead of ammonium sulfate.

SUMMARY

Plants on low to medium saline soils suffer from nutritional stress as can be shown by plant analytical data obtained from fields with different degrees of growth reduction. Wheat plants on southern Italy saline soils high in Na and Mg contain harmful surplus of Na but not of Mg, and become deficient in K and Ca with increasing salt content of the soil.

The interpretation of plant nutrient data requires probably a modification of some limiting values, e.g., for K higher contents seem to be required for optimum supply compared with non-saline soils. Special fertilization according to plant diagnosis is suggested for the improvement of the nutritional situation.

LITERATURE

Bernstein, L., and H. E. Hayward. 1958. Physiology of salt tolerance. Ann. Rev. of Pla. Phys. 9:25-46.

Chang, C. W., and H. E. Dregne. 1955. Effect of exchangeable sodium on soil properties and on growth and cation content of alfalfa and cotton. Soil Sci. Soc. Amer. Proc. 19:29-35.

Elgabaly, M. M. 1961. Studies on salt tolerance and specific ion effects on plants. Salinity problems in the arid zones. Proc. of the Teheran Symp. Arid Zone Res. 14:169-174, UNESCO Paris.

Finck, A. 1976. Pflanzenernährung in Stichworten Hirt, Kiel 1976.

Finck, A., and U. Schleiff. 1972. Salt tolerance of crops under ecological conditions in Southern Italy with special reference to high magnesium content in soil. Proceed. Salinity Conference Cairo.

Heimann, H. 1966. Plant growth under saline conditions and the balance of the ionic environment. In H. Boyko, ed. **Salinity and Aridity. Dr. W. Junk Publishers, the Hague.**

Epstein, E. and C. E. Hagen. 1952. A kinetic study of the adsorption of alkali cation by barley roots. Plant Physiol. 27:457-474.

Kafkafi, U. 1973. Nutrient supply of irrigated crops. Arid Zone Irrigation, 177-188, Springer, Berlin.

Loneragan, J. F., and K. Snowball. 1969. Calcium requirements of plants. Aust. J. agric. Res. 20:465-478.

Oertli, J. J. 1976. The physiology of salt injury in plant production. Z. Pflanzenern. Bodenk. 195-208.

Poonia, S. R., and D. R. Bhumbla. 1973. Availability of Ca from $CaSO_4$ in a highly saline sodic soil. Plant and Soil 38:675-678.

Rains, D. W. 1972. Salt transport by plants in relation to salinity. Ann. Rev. Plant Physiol. 23:367-388.

Ravikovitch, S., and A. Porath. 1967. The effect of nutrients on the salt tolerance of crops. Plant and Soil 26:49-71.

Ravikovitch, S., and J. Navroth. 1976. The effect of Mn and Zn on plants in saline soil. Soil Sci. 121:25-31.

Röber, R. 1969. Untersuchungen über die Wirkung von Chloriden und Nitraten auf junge Gersten-, Tomaten-, Azaleen- und Maispflanzen. Diss. Hannover.

Schleiff, U., and A. Finck. 1976. Untersuchungen zur Bedeutung des Ernahrungszustandes von Kulturpflanzen für ihre Salztoleranz. Z. Pflanzenern. Bodenk, 281-292.

Strogonov, B. P. 1964. Physiological basis of salt tolerance of plants. Israel Progr. Sci. Translat. Jerusalem.

Van den Berg, C. (Editor). 1973. Plants in relation to water-logging and salinity. International Sourcebook on Irrigation, Drainage and Salinity. FAO/UNESCO.

Wichmann, W. 1976. Ermittlung von Grenzwerten der Pflanzenanalyse zur Kennzeichnung der Mg-Versorgung von Getreide in Schleswig-Holstein. Diss., Kiel.

PROBLEMS OF MANAGING GEOTHERMAL WATERS FOR IRRIGATION

H.B. Peterson 1/ and J.L. Shupe 2/

INTRODUCTION

With the development of geothermal water as a source of energy, there will be considerable "spent water" available for other purposes. In the United States most of the known geothermal basins are in the Western States where water is scarce and the need and temptation to use spent geothermal water for irrigation is great. This will also likely be true in other parts of the world. In this discussion we are concerned with minimizing or avoiding adverse effects caused by chemical constituents and not the possible benefits or damage to crops from the heat in the water.

Most systems of evaluating the quality of water for irrigation give consideration to those constituents that adversely affect the crop and/or the soil. We feel it is also necessary to consider components that either directly or indirectly affect animals, people receiving waters and conveyance systems. In many parts of the world, whenever water is placed in a ditch or stream it may become a supply source for animals and people as well as crops.

Fig. 1 shows the possible routes of each pollutant in the water that we feel should be given careful consideration before the water is released for irrigation.

Compositon of waters

Geothermal waters are characteristically contaminated with chemical impurities of underground origin. The concentrations of salts vary from a few hundred mg/l to many thousands. One spring in Utah contains 37,504 mg/l (Mundorf, 1970) and others may be higher. The most common impurities are:

sodium
potassium
lithium
calcium
magnesium
ammonium
silica
chloride
fluoride
borate
sulfate
carbonate
hydrogen sulfide
bicarbonate
carbon dioxide

There are often other impurities of particular concern such as arsenic, molybdenum, selenium, and the heavy metals.

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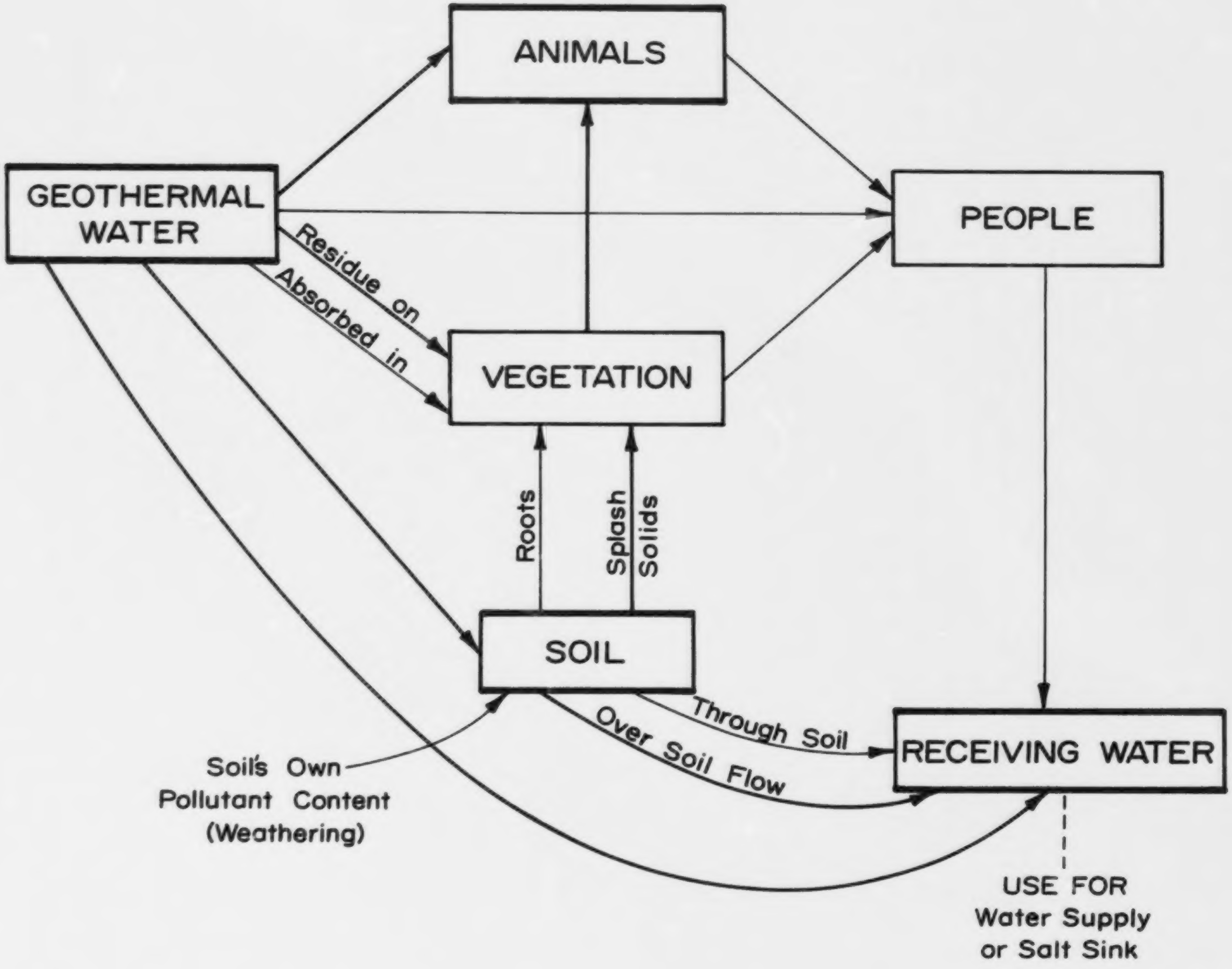
ANIMALS
GEOTHERMAL WATER
PEOPLE
Residue on
Absorbed in
VEGETATION
Roots
Splash Solids
SOIL
Through Soil
Over Soil Flow
RECEIVING WATER
Soil's Own Pollutant Content (Weathering)
USE FOR Water Supply or Salt Sink

Fig. 1. Diagram showing the possible routes of pollutants in geothermal water.

Boron concentrations of 49 mg/l in the U.S., 99 in New Zealand, and 131 in El Salvador have been reported. Lithium concentrations of 10-15 are not uncommon and as much as 320 have been reported in California (Ellis, 1975; Sigvaldason, 1973). Arsenic values of 3, 4, and 5 are apparently prevalent with as much as 38 and 48 in water of some wells (Ellis, 1975). We have heard there are waters with fluroide concentrations as high as 90 mg/l being used for irrigation but as yet this has not been verified.

Total Salts

Choosing which salty water can be safely used for irrigation is always a problem. With geothermal waters, the decision is further complicated by the fact the water is hot and there is some advantage in sprinkling to cool the water; in addition, the topography of many lands is more suited to irrigation by sprinkling than by surface irrigation. Unfortunately, a given crop is more sensitive to salty water when that water is sprinkled. We also know that at a slow rate of application the crop damage is greater. High air or water temperatures and low humidity are also conducive to greater damage from sprinkling with salty water. At the present time we are not prepared to specify what salt concentration, air and water temperatures, and what application rate are satisfactory for specific crops. However, such information is needed for the proper management of any warm saline waters.

We are particularly concerned with the "salt loading" effects of "imported water" from deep in the earth. Salt in rivers and from relatively shallow wells is considered to be in the normal hydrologic system we are trying to manage. Salt from geothermal well development may be considered as introduced, or imported. To offset the adverse effects we would like to propose that wherever possible the concentrated drainage waters from irrigated land go directly to a salt sink. In the vicinity of geothermal wells these waters may be reinjected into the geothermal basin to reduce the hazards from subsidence. The geothermal basins might also be used as salt sinks for other saline waters as a means of deporting salt.

Sodium absorption ratio

The sodium hazard from using geothermal waters is often great and difficult to evaluate. The solubility of many of the constituents is a complex function of temperature and pressure. The composition of geothermal waters often changes from the well head to the user point. This is illustrated by the crystalization of calcium carbonate in the pipe carrying geothermal water in Fig. 2. In determining the probable sodium hazard as indicated by the SAR, we strongly recommend using a corrected value such as proposed by Ayers (1975).

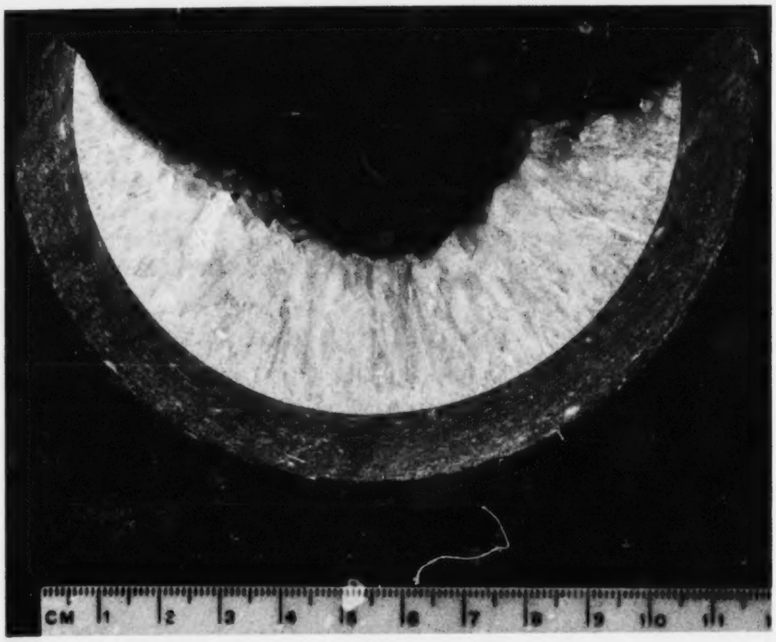

Figure 2. Calcium carbonate crystals formed in transite pipe. The precipitate also contains 75 ppm F.

Specific Salts

In this paper, we will not discuss the possible problems with salts of arsenic, boron, and heavy metals. We will, however, consider some of the complexities encountered with flourides since F is often prevalent in the water and its possible adverse effects frequently are overlooked by the users.

While assessing the problem of flouride toxicosis in the Western States, data from 322 geothermal waters were compiled (Table 1). These data indicate that at least 78 percent of the waters contained quantities greater than the safe limit for people (Table 2). It is unlikely that most of these particular waters will be used for potable purposes for large numbers of humans but animals will often use them. Wild as well as domestic animals may be exposed. In Figure 3 is shown the damage to the incisor teeth of an elk from ingestion of excessive F in the geothermal water. Dairy cows that drank water for 10 to 12 months from a warm well containing 11.6 mg/l F developed a characteristic lameness often associated with marked to severe flouride toxicosis (Figure 4). In another case study located near the above dairy, beef cattle have severely damaged teeth as a result of drinking geothermal irrigation water containing 11 mg/l F.

Table 1. Fluoride in geothermal spring and well waters.

Location	Ranges mg/l	Intervals of F Content - mg/l 0-2	 2.1-10	 10.1-30
		Frequency		
California	<0.1 - 12	31	34	2
Idaho	.1 - 30	35	44	45
Nevada	<0.1 - 19	6	30	9
Oregon	.8 - 21	7	19	6
Utah	.3 - 14	22	23	2
Wyoming	2 - 10	2	4	1
Totals		103	154	65
Percentages		32	48	20

Table 2. Maximum levels F for potable waters.

Temperature† Degrees Celsius	mg/l
12.0 and below	2.4
12.1 to 14.6	2.2
14.7 to 17.6	2.0
17.7 to 21.4	1.8
21.5 to 26.2	1.6
26.3 to 32.5	1.4

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† Annual average of maximum daily air temperatures. Federal Register, December 24, 1975.

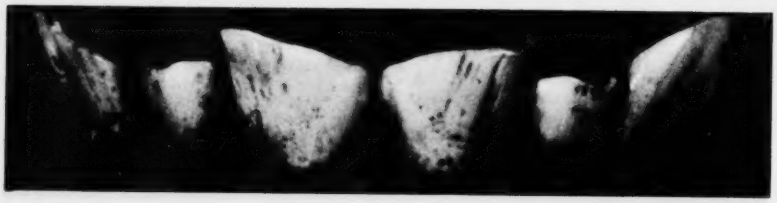

Figure 3. Dental Fluorosis in permanent incisor teeth of elk. Note mottling, chalky enamel, horizontal pitting and bilateral nature of abnormal abrasion.

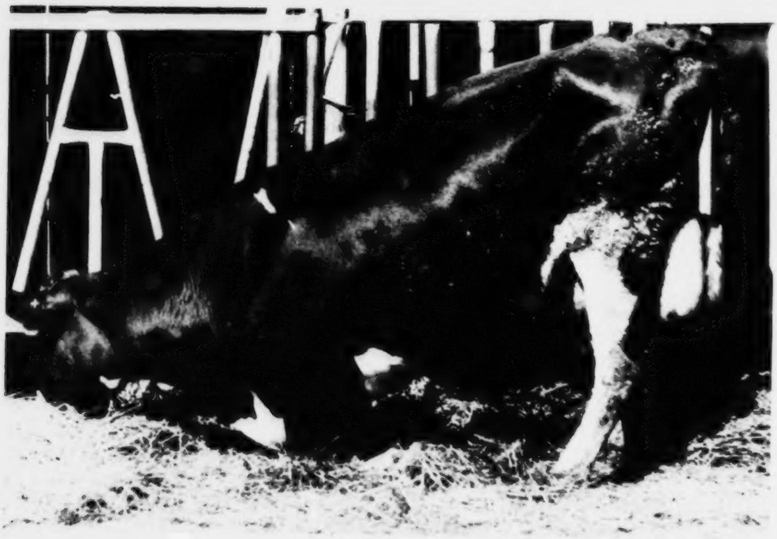

Figure 4. Holstein cow with severe fluoride induced bone lesions and lameness. Abnormal position is characteristic of severe osteofluorotic lameness.

Evaluating the probable hazard to animals is more complicated than for humans. First, the tolerance levels for animals can be greater than for people because there is little concern for the cosmetic effects of F on animal's teeth. Second, animals may obtain large amounts of fluoride from both water and feed. The amount of F ingested and assimilated from the water depends on the solubility, concentration, and quantity consumed. The quantity of water consumed is partially dependent on air temperature (Fig. 5), Dyer and Johnson, 1976). The dairy and beef animals referred to above live where the summer temperatures often reach 38°C.

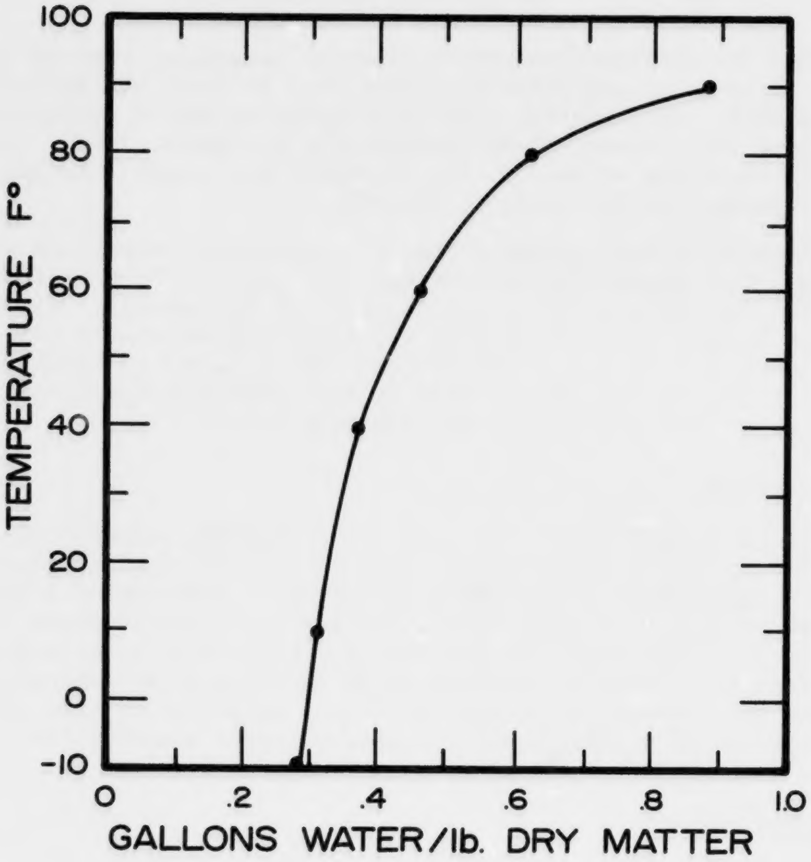

Figure 5. Water intake by beef cattle at different temperatures.

The fluoride in forages resulting from the F in the water used for irrigation is dependent on the concentration, method of water application, and probably the pH of the soil. When water high in fluorides is applied directly to neutral or alkaline soils the F is precipitated in a low solubility form and very little F enters the roots and is translocated to the tops (Daines, Leone, and Brennan, 1952; MacIntire, 1952). Plants sprinkled with water containing F may have the fluorides adhere to the foliage or be absorbed by the foliage. We are attempting to determine how much is adhering to the foliage and how much may possibly be washed off. Sprinkling may also cause splashing from the soil surface so contamination from soils high in F may get on the forage.

The whole fluoride toxicosis problem is further complicated by the fact that the different inorganic fluoride compounds vary in their degree of toxicity and animals species vary in their susceptibility to fluorides. Equivalents of NaF are approximately 50 percent more toxic than CaF_2 (Shupe, Miner, Harris, and Greenwood, 1962). Many fluoride compounds of Na, Ca, Si, Al, and P are possible in geothermal waters but difficult to identify.

We feel there is good evidence that F in geothermal water can adversely affect people who may consume the water for long periods of time, but the probability is not as great as for animals. Fluoride can harm animals directly through the water and indirectly from large quantities in and on the forage. The F hazard to receiving waters is largely from direct flow or from overland flow from irrigation runoff and not from ground drainage water.

Pipe Corrosion

When the geothermal waters are used for irrigation and applied through a sprinkler system it is usual to utilize aluminum pipe. The warm temperature of the water and probable heavy metal content are conducive to electrochemical reactions resulting in rapid corrosion. It is difficult to specify the concentrations and compositions that will cause corrosion because of the complex interactions. It would be advisable to obtain an opinion or guarantee from the pipe supplier of manufacturer. We have observed new pipelines that have lasted for less than one year.

Analytical Problem

When determining the benefits and possible hazards resulting from the use of chemically laden water it is essential to have reliable analytical data. For numerous reasons such data is not always easy to obtain for geothermal waters. The actual compositon of the water can change and when the data indicate a change it may be real or an analytical variance. Also, different analysts using the same sample often do not report the same values, particularly for some elements such as F.

The composition of water may change from the well head to the user point, and the user points of the water from the same source are different.

To specifically illustrate a problem, we have data from a well to be used for power development and irrigation. From one laboratory we have results on one day of samples run at the same temperature and pressure with values for nickel of 1.0, 0.4, 0.4, 0.6 mg/l. For a different day with samples at different temperatures, pressures and time after sampling the values are trace, 3.2, 2.1, and 5.7 mg/l. For the same samples the variation of boron was from 1.2 to 8.4 and for fluoride from 7 to 10.4.

With such variable data we are not sure whether or not we have a problem of too much Ni and B, but we do have some analytical problems and if you are attempting to manage the use of geothermal waters for irrigation, you will be fortunate if you avoid similar experiences.

LITERATURE CITED

Mundorf, J. C. 1970. Major thermal springs in Utah. U. S. Geol. Survey Water Resources Bull. 13.

Ellis, A. J. 1975. Geothermal systems and power development. American Scientist 62, pp. 510-521.

Sigvaldason, Gudmundur F. 1973. Geochemical methods in geothermal exploration. Geothermal Energy: Review of Research and Development, (Earth Science 12) UNESCO, Paris, France.

Ayers, Robert S. 1975. Quality of water for irrigation. Specialty Conference, Logan, Utah. American Society of Civil Engineers, New York. pp. 24-55.

Dyer, I. A., and R. J. Johnson. 1976 Water quality for livestock: a review of the CAST task force report. Veterinary Toxicology 18: No. 2, pp. 65-71.

Daines, Robert H., Ida Leone, and Eileen Brennan. 1952. The effect of fluorine on plants as determined by soil nutrition and fumigation studies. Air Pollution Proceedings of the United States Technical Conference on Air Pollution, Chpt. 9, McGraw-Hill Book Company, New York.

MacIntire, Walter H. 1952. Air versus soil as channels for fluoric contamination of vegetation in two Tennessee locales. Air Pollution Proceedings of the United States Technical Conference on Air Pollution, Chpt. 4, McGraw-Hill Book Company, New York.

Shupe, J. L., M. L. Miner, L. E. Harris, and D. A. Greenwood. 1962 Relative effects of feeding hay atmospherically contaminated by fluoride residue, normal hay plus calcium fluoride, and normal hay plus sodium fluoride to dairy heifers. Amer. Jour. of Vet. Res. 23 No. 95, pp. 777-787.

SALT TOLERANCE OF BEANS UNDER A SAND MULCH CULTURE

Miguel Angel Parra and Gonzalo Cruz Romero [1]

INTRODUCTION

Under controlled growth conditions some studies have shown that climate modifies crop response to the salinity of the medium. Under low evapotranspiration demands (low temperature and/or high relative humidity), plant tolerance to salinity generally increases (Hoffman and Rawlins, 1971; Hoffman, et al., 1971; Nieman and Poulsen, 1967). However, available information on the effect of climate on salt tolerance in field conditions is scarce and is largely based on comparisons of salt tolerance data obtained in different climatic areas. This information has been obtained under varying conditions of soil, type of salinization, water management, etc., making quantitative interpretation of results difficult. When more than one growth season in a year is possible for one crop, it seems most desirable to know the influence of climate on salt tolerance of plants when all other field and management conditions remain unchanged.

In southeastern littoral Spain, green beans, one of the most important crops, can be grown in fall or spring under a sand mulch culture (Mendizábal and Verdejo, 1968). The poor quality of the irrigation water and the low application doses makes it hazardous to grow low salt tolerance crops, such as Phaseolus sp. (Gauch and Wadleigh, 1942; Bernstein and Ayers, 1951; Bernstein, 1974).

In this study the influence of growth season and salinization time on salt tolerance of two bean varieties under field conditions such as those used in southeastern Spain have been investigated. The salt tolerance of both varieties in the germination stage was also studied.

MATERIAL AND METHODS

Details of the three field experiments carried out to study salt tolerance of two varieties of beans are summarized in Table 1.

Plants were grown in a polyethylene-covered enclosure with artificially-induced salinity in a calcareous alluvial loam soil whose characteristics are given in Table 2. Four salinity levels, including the check, were reached in all the experiments with four replications. The experimental design consisted of 2 x 2 m plots arranged in random blocks (exp. A) and factorial split plots where the effect of cultivar was also studied (exp. B and C).

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Table 1: Description of **Field Experiments**

Experiment, Date, and Cultivars	Treatments	Salt Content of Irrigation Waters Added NaCl	Added $CaCl_2$	Total	First Irrigation with Saline Water (Days after Planting)
		-------ppm	----------	----------	
A	0	0	0	600	42
Spring, 72	I	880	1000	2480	
Kora	II	1460	3230	5290	
	III	1870	5730	8200	
B*	0	0	0	600	21
Fall, 72	I	880	1000	2480	
Kora and	II	1460	3230	5290	
Garrafal	III	1870	5730	8200	
C	0	0	0	600	20
Spring, 73	I	1140	2080	3880	
Kora and	II	1660	4430	6690	
Garrafal	III	1970	7030	9600	

* In 4th, 5th and 6th irrigation, the salt content of the water used was increased by 50% of that indicated.

Saline irrigation waters were prepared by adding the amounts of NaCl and $CaCl_2$ specified in Table 1 to tap water having an electrical conductivity (EC) of 0.9 mmho/cm and Sodium Adsorption Ratio (SAR) of 0.7 to obtain waters of increasing EC and constant SAR of 4. The average composition of the tap water in meq/l was: Ca = 4.5; Mg = 3.4; Na = 1.5; K = 0.5; CO_3H = 7.0; SO_4 = 2.0; and Cl = 0.9. In order to obtain plot salinization faster than that obtained in exp. A, the amount of salt added to the waters was increased by 50% in three of the irrigations of exp. B and in a constant amount (1400 ppm) in all the irrigations of experiment C.

Prior to seeding, 4 Kg/m^2 of farmyard manure and 0.4 Kg/m^2 of complex fertilizer 12-12-24 were mixed with the surface soil. Thereafter, a layer of farmyard manure, at a rate of 4 Kg/m^2, was spread on the leveled surface placing on top of it an 8 cm thick layer of siliceous sand (between 3 and 6 mm in diameter). Seeding was done in rows 60 cm apart, placing several seeds in holes which were 10 cm apart within the rows. After germination plants were thinned, leaving one for each hole 20 cm apart.

Table 2: Soil properties

Depth	Organic matter	Carbonates	Sand	Silt USDA	Clay	Bulk density	pH 1:2.5		CEC	Water content and tension at so-called Field Capacity	
							H_2O	KCl			
cm	%	%	%	%	%	g/cm^3			meq/100 g	%	cb*
0-30	1.45	25.6	37.5	46.0	16.5	1.30	8.7	8.0	17.2	22	10
30-60	0.81	24.4	37.5	43.5	19.0	1.34	8.7	7.9	--	19	13
60-90	0.52	27.2	40.0	41.0	19.0	1.36	8.3	8.0	--	-	-
90-120	0.46	25.9	37.5	41.5	21.0	1.36	8.5	7.9	--	-	-

* centibars

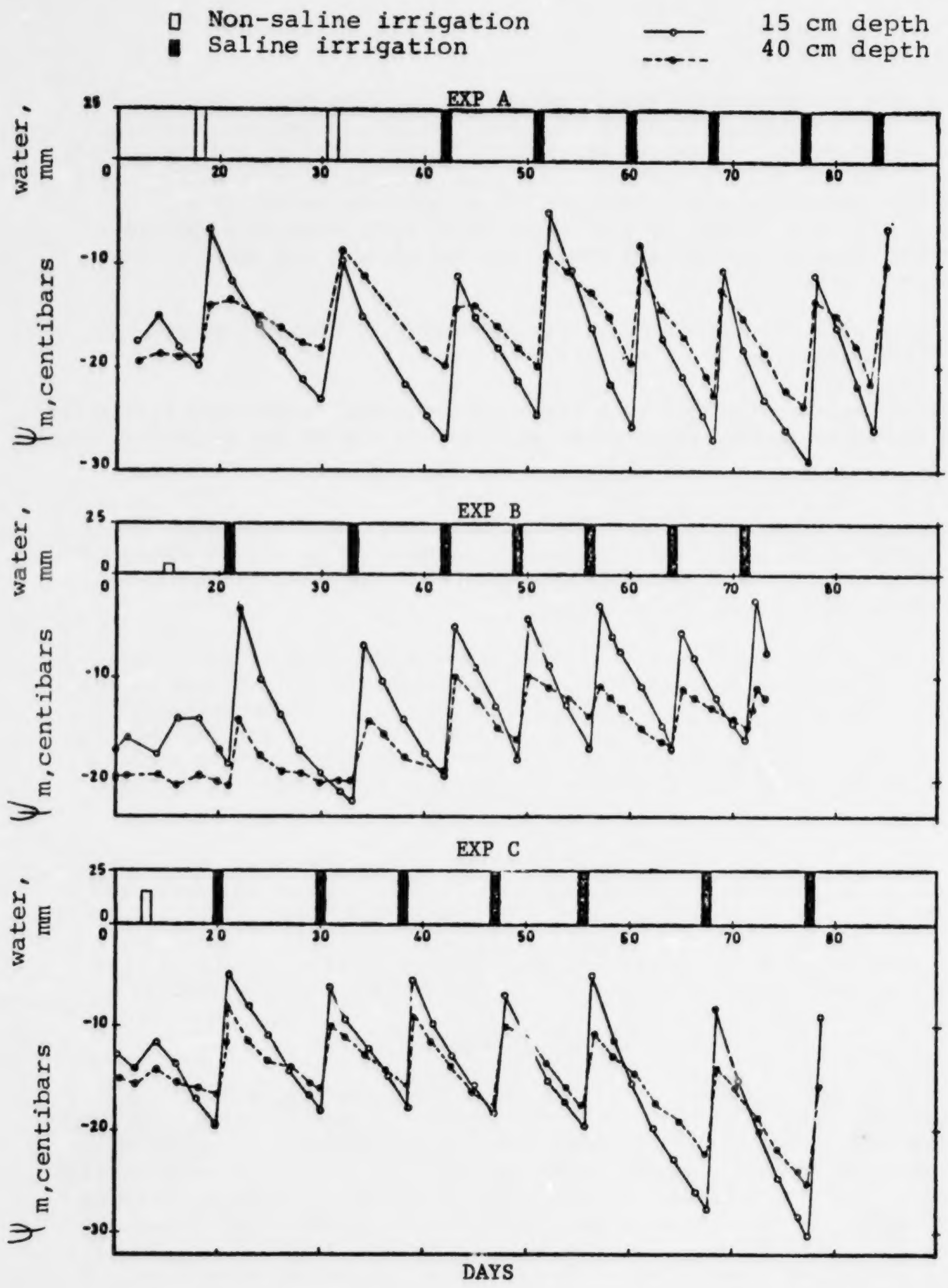

Figure 1. Irrigation regimes and soil water matric potentials at 15 and 45 cm depth.

Plants were irrigated when matric potentials at 15 cm depth were between -15 and -30 centibars. Figure 1 shows the irrigation regimes in the three experiments, the time at which salinization started, and the amount of water used in each irrigation. The first irrigation with saline water was always done with water containing half the amount of salt scheduled. Every 20 days 15 g/m^2 of 10-10-25 fertilizer were applied and every other irrigation 100 ppm of calcium nitrate was added to the irrigation water.

After each growth season the soil was chemically sterilized; it was also flooded to leach out the salts.

Duplicate soil samples from each treatment were taken after each irrigation at 20 cm intervals to a depth of 60 cm to measure EC of the saturation extract (EC_{se}).

Harvesting was done in several successive pickings when pods were ripe for green consumption, fresh and dry weights being determined each time. The dates of each picking and other characteristics of crop development are given in Figure 2.

Duplicated foliar samples from each treatment were taken before salinization, after three irrigations with saline waters and at the end of the culture. The method of Ulrich (1956) was used to determine cations, while chloride extraction was accomplished by the Brown and Jackson method (1955). Ca and Mg were complexometrically titrated with disodium salt of EDTA; Na and K were determined by flame photometry; Cl by Mohr titration.

Salt tolerance of two cultivars of beans at germination stage was studied through a factorial 4 x 2 assay with four replications as follows: 500 g of soil were placed in a Petri dish and watered with four saline solutions (Table 1, exp. A) up to 0.16 g H_2O/g soil, and 15 seeds per dish were sown. The dishes were kept in a growth chamber at 25° C, observing the numbers of seeds that germinated and the time elapsed from planting.

RESULTS AND DISCUSSION

In studying salt tolerance of plants under field conditions some kind of compromise has to be arrived at in relation to the following: 1) length of time of exposure of a crop to salinity conditions; and 2) degree of heterogeneity in salt distribution in the rooting zone of the soil profile. Figure 3 shows the patterns of soil salinity changes throughout the three experiments. In the top 40 cm mean soil salinity higher than 2.5, 4 and 6 mmhos/cm at 25° C (EC_{se} corresponding to the treatments I, II and III, respectively) was found after 47-55 days from the seeding date in exp. B and C ("early" salinization) and after 70-80 days in exp. A ("late" salinization). Therefore, plants were exposed to soil salinity levels higher than the above mentioned values: 8-18 day period in exp. A, and 27-32 and 23-31 days in exp. B and C, respectively.

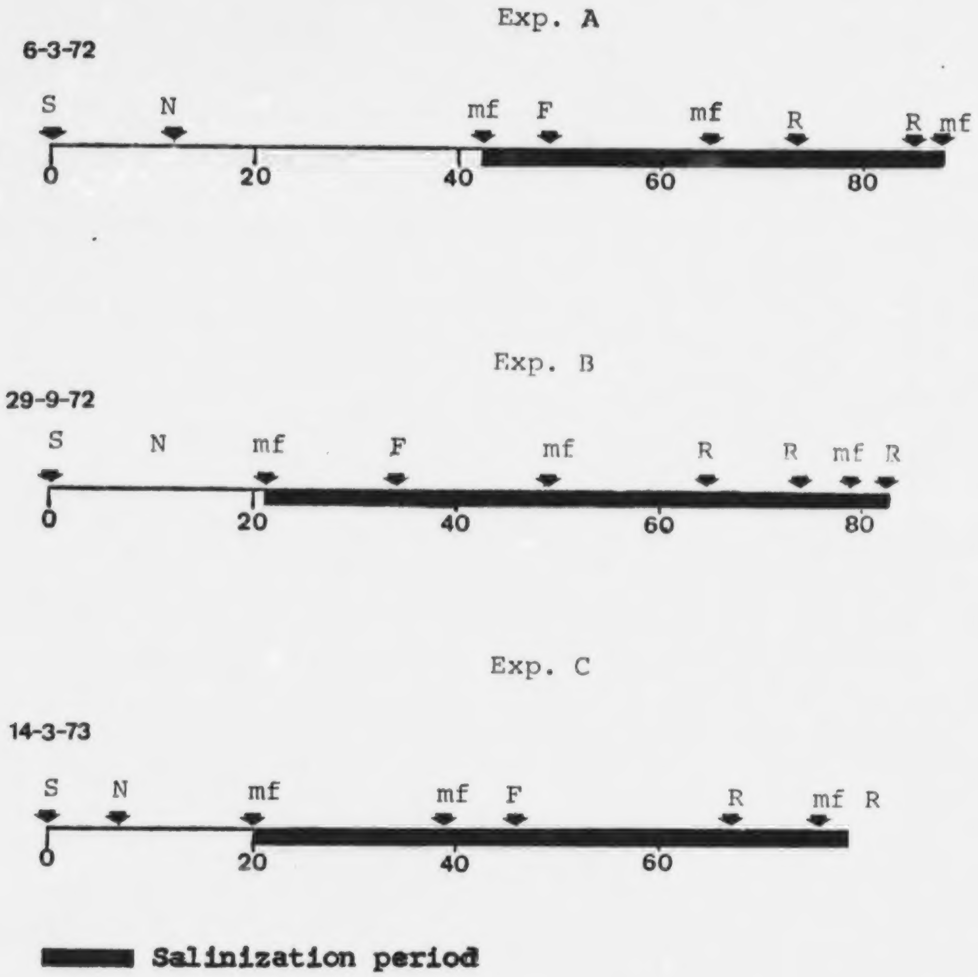
Exp. A
6-3-72
S
N
mf
F
mf
R
R
mf
0
20
40
60
80
Exp. B
29-9-72
S
N
mf
F
mf
R
R
mf
R
0
20
40
60
80
Exp. C
14-3-73
S
N
mf
mf
F
R
mf
R
0
20
40
60
Salinization period

Figure 2. Characteristic dates of crop development and of foliar sampling. (S: seeding; N: emergence; F: flowering; mf: foliar sampling; R: harvest).

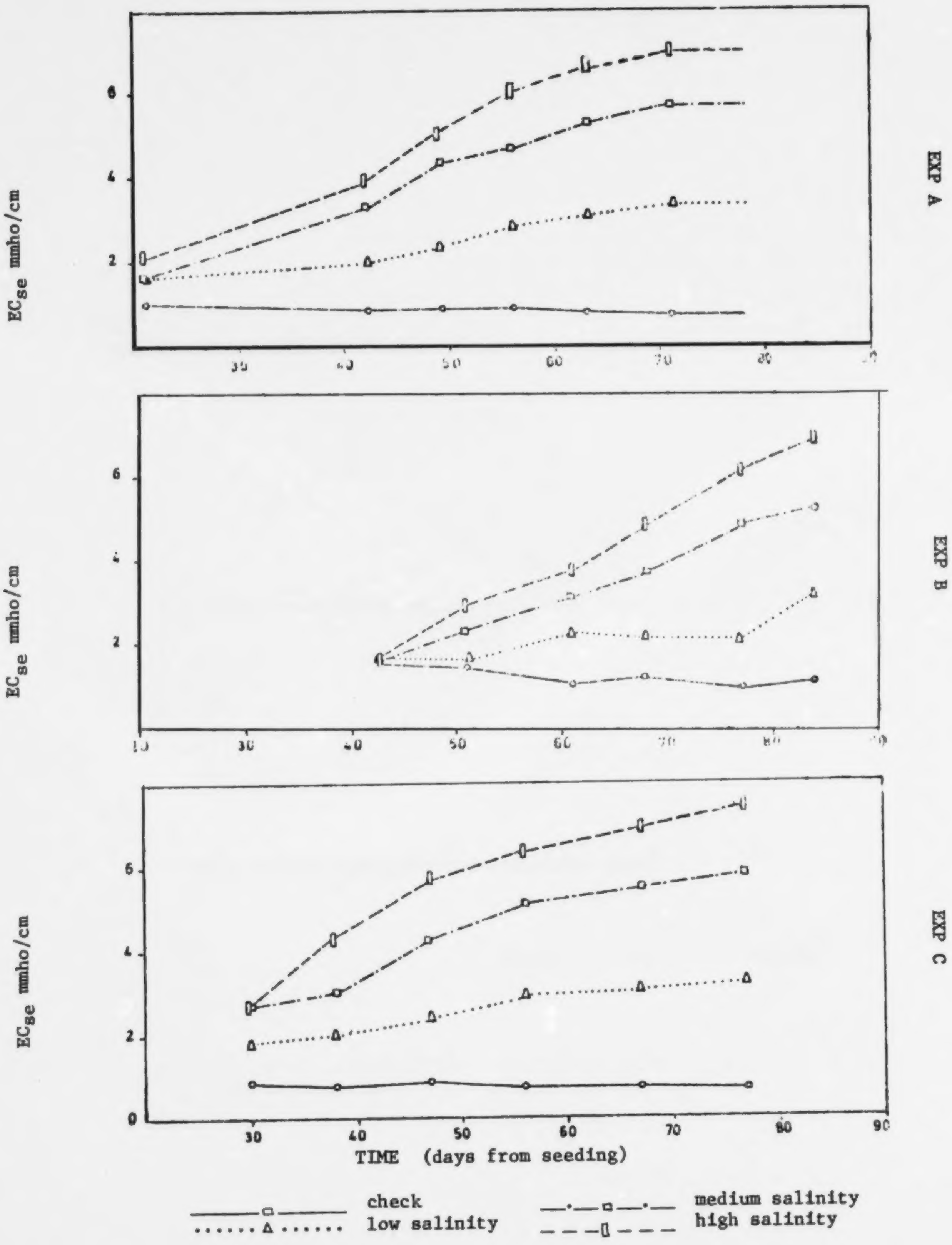

Figure 3 . Soil salinity changes as a function of time.

A possible measure of the degree of heterogeneity of salt distribution in the soil profile is the soil salinity distribution index, which is the ratio of the EC_{se} of the upper and lower soil strata explored by roots. Table 3 shows the values of such a ratio as a function of the number of saline irrigations for each treatment and experiment. From the third irrigation on there was always an increasing homogeneity (decreasing values of the ratios) in salt distribution within the soil profile. Maximum homogeneity was obtained in experiment B, followed by C and A. We attributed this fact to the lower irrigation efficiency, that is, to the magnitude of salt leaching by mass flow, which must have decreased in the order B>C>A. This hypothesis is supported by the trend of soil/water matric potentials shown in Figure 2, which are, in a certain way, inversely proportional to irrigation efficiencies (potentials decreasing B>C>A).

Table 3: **Soil salinity distribution index versus number of saline irrigations, treatment and experiment**

Experiment	A				B				C		
Number of Irrigations	1	3	5	6	1	3	5	7	3	5	7
Treatment											
I Low	3.0	3.75	3.5	2.3	1.2	1.9	1.6	1.5	3.5	2.5	2.2
II Medium	2.6	3.90	2.3	1.8	2.0	2.0	1.4	1.3	2.2	2.3	1.7
III High	4.2	11.00	2.8	1.6	3.8	2.8	1.8	1.1	3.3	2.3	1.7

In all the saline treatments, SAR values of soil saturation extracts determined in soil samples collected at the end of the harvest were very close to predictions, on the order of 3 to 4. Although in check plots SAR were lower (on the order of 1 to 2), it does not seem likely that such a small difference could have differentially affected yields. Bernstein and Pearson (1965) reported detrimental effects of adsorbed sodium on bean yields at exchangeable sodium percentages higher than 10%.

Separate yield data for each picking, and their statistical significance, are given in Tables 4 and 5. In all experiments increasing soil salinity significantly decreases absolute yields, and increases yields of first picking and dry pod matter. The adverse effect of salinity on yields was shown primarily by a reduction of the number of pods per plant, although under high evapotranspiration demands and early salinization (exp. C) pod size was also significantly reduced.

Lunin et al. (1961a, b) used first picking yields expressed as a percentage of total yields as a maturity index. They found that salinity brought

Table 4: Yield Data. Kora (K) and Garrafal (G) green beans.

Exp	Treatment	Yield g/green pods/plot		Relative yield		Yield of first picking, % of Total		Average weight of pods g/pod		Dry matter of pods g/100 g of fresh weight	
		K	G(1)	K	G(1)	K	G(1)	K	G	K	G
A	0	9.82		100.0		68.0		7.44		20.00	
	I	9.45		96.9		71.7		7.45		23.10	
	II	8.17		83.6		80.0		7.45		25.60	
	III	7.56		77.2		86.3		7.25		27.10	
B	0	2.34		100.0		59.9		6.35	8.71	7.36	6.61
	I	2.24		95.8		59.3		6.43	9.30	7.76	7.22
	II	2.09		89.5		61.0		6.34	8.76	8.03	7.65
	III	1.77		75.6		64.0		6.45	9.21	7.93	7.68
C	0	4.16	3.45	100.0	100.0	30.0	60.4	6.57	9.68	11.21	8.31
	I	3.81	2.87	91.4	83.2	35.2	58.6	6.48	8.95	11.53	9.04
	II	2.81	2.61	67.6	75.6	37.8	68.3	6.22	8.92	11.87	9.44
	III	2.16	1.77	51.9	51.3	40.9	68.8	5.85	8.45	11.97	10.46

(1) Due to a virosis that unequally affected Garrafal plants in experiment B, yield data are not given.

(2) Averaged data for all the pickings.

about a delay in ripening, this effect being more pronounced for a given salinity level, when salinization was gradual, than when it was sudden. However, in our work the increasing yields of first pickings and dry pod matter observed with increasing soil salinity in all the experiments (Tab. 4) suggest that soil salinity accelerates fruit ripening. It must be pointed out that the progressive soil salinization used in our experiments could have had a more pronounced adverse effect on yields of late pickings, rather than on early ones. Our results clearly conflict with those reported by Lunin et al. (1961a, b).

Table 5: Statistical Significance of Harvest Data

	Absolute Yields			Yield of First Picking % of Total			Average Weight of Pods			Dry Matter of Pods		
Experiment	A	B	C	A	B	C	A	B	C	A	B	C
Salinity	*	*	**	**	*	*	ns	ns	*	**	**	**
Cultivar	-	ns	ns	-	**	**	-	**	**	-	ns	**

*: differences significant at 5% level
**: differences significant at 1% level
ns: differences not significant

Although no significant varietal differences in total yields were observed, Kora yielded significantly less in the first picking than Garrafal, which produced larger and more succulent pods. The interaction effect, salinity x cultivar, was not significant for any of the data analyzed.

After plant roots extracted from the soil by the monolith method were inspected, soil salinity was calculated by a geometric means of EC_{se} of the soil strata in the average soil rooting zone (0-40 cm), for the last 40 days of each culture. That was the period in which plants were irrigated with saline water in the late salinization experiment. Kirkham et al. (1969), Shalhevet and Bernstein (1967) and Shalhevet et al. (1969) have shown that yields of beans, alfalfa and peanuts respectively, were favorably correlated with mean soil salinity calculated in that way, when salts were heterogeneously distributed in the soil profile. However, Bernstein and Francois (1973) further reported that fresh matter production of alfalfa was better correlated with the salinity of the least saline soil strata explored by roots than with mean soil salinity.

Linear regression lines and corresponding equations of relative yields and mean soil salinity are shown in Figure 4. Under early salinization regimes and high evapotranspiration demands, yields of two bean cultivars were reduced by 50% of the maximum at EC_{se} of 6 mmhos/cm. This latter

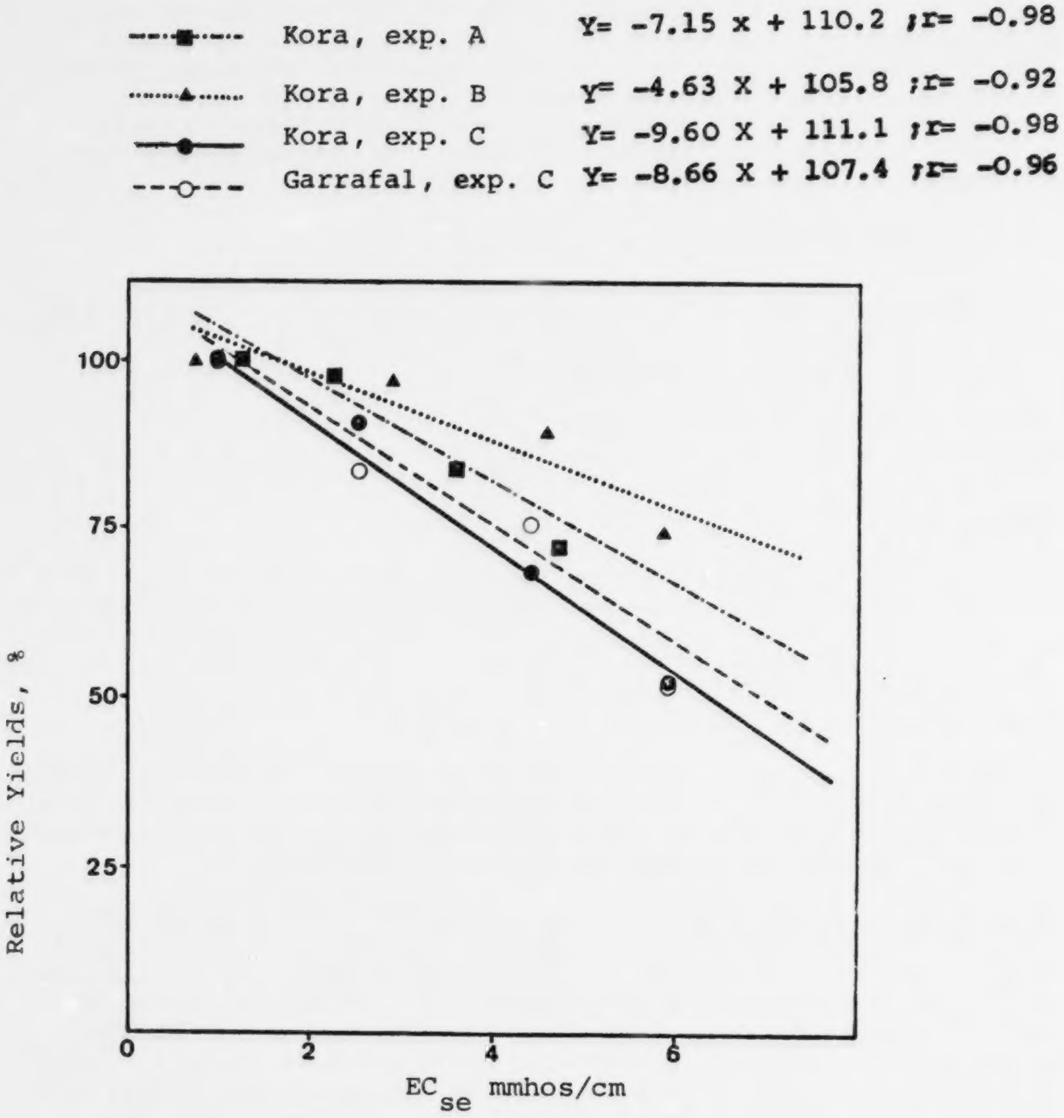

Figure 4. Relationship between relative yields of green pods and mean EC$_{se}$ of the top 40 cm of soil

figure means an almost two-fold higher salt tolerance than that generally reported for Phaseolus sp. (Bernstein, 1974). Furthermore, salt tolerance was increased by almost 100% when the crop was grown under low evapotranspiration demands (fall culture). This result agrees with those reported by Nieman and Poulsen (1967) and Hoffman and Rawlins (1971) under controlled conditions, although they estimated production by fresh weights of aerial parts. An additional 30% salt tolerance increase was observed when soil salinization was delayed twenty days, a result in agreement with those reported by Lunin et al. (1961a) and Meiri and Poljakoff-Mayber (1970) who found lower yields in plants with increasing length of exposure to salinity conditions.

Millar and Gardner (1972) have reported decreasing growth rate of beans at decreasing, but relatively high, soil water matric potentials. Therefore, it could be argued that differences in salt tolerance obtained in different experiments could be partially explained by varying irrigation regimes. This could well be the case if salt tolerance of the crop were a very sensitive function of water matric potential in the interval of 0 to -30 centibars; it does not happen when the period to which the plants are exposed to relatively low values of matric potentials is very short (Parra and Cruz, 1976).

The results of foliar analyses reported in Figure 5 show that cation concentrations in leaf dry matter were not affected by the growing season (fall or spring). Of the two cations which predominated in the irrigation water, Ca and Na, the amount of Ca in the leaves increases with increasing soil salinity, while the amount of Na was independent of salinity. This observation confirms Jacoby's (1964), which postulated a mechanism of Na exclusion in leaves, at least at high Ca levels. Foliar concentration of Mg did not show any clear trend in relation to salinity, while K concentration diminished when salinity increased, as could be expected from the well-known competition between Ca and K. The amount of Cl in leaves increased with increasing salinity and for a given salinity level was higher at high evapotranspiration demands. The increments of Cl in leaves were not compensated by proportional amounts of cations. Bernstein (1963), among others, has shown that under saline conditions Cl replaces organic anions to keep electrical balance in plant sap. There were no varietal differences in leaf chemical composition, except that the final levels of Ca in Kora leaves were slightly higher than in Garrafal.

The effect of salinity on bean germination (Tab. 6) was two-fold: it reduced the percentage of germinated seeds and increased the germination time. Garrafal was more tolerant of salinity at germination than Kora. A 50% decrease of relative germination for both cultivars was found at EC_{se} of 8.3 and 9.2 mmhos/cm, respectively.

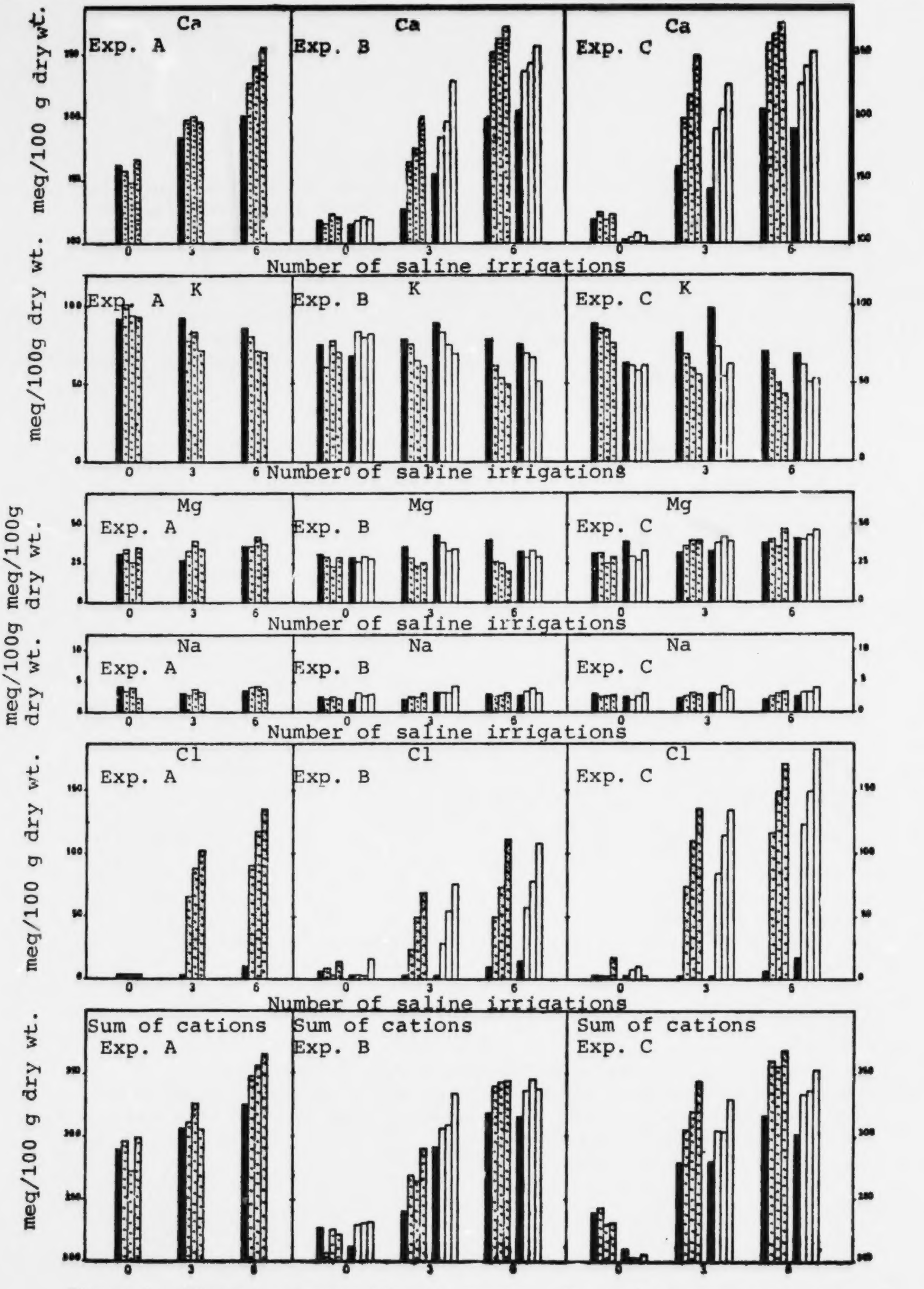

Figure 5. Element concentrations in leaves. For each element and experiment results for each cultivar are given indicating in x-axe the number of saline irrigations carried out up to the sampling date.

Table 6: Salt tolerance during germination. Kora (K) and Garrafal (G) cultivars

Treatment	EC_{se}	Relative germination		Time for 50% germination	
		K	G	K	G
	mmhos/cm	%	%	days	
0	1.18	100.0	100.0	5.5	4.3
I	4.32	85.2	84.5	6.0	4.6
II	7.26	63.0	72.4	8.1	5.6
III	9.62	37.0	43.1	10.0	7.7
Statistical Significance					
Salinity		*		**	
Cultivar		**		**	

SUMMARY

Salt tolerance of two cultivars of beans grown for green consumption under a sand mulch culture has been studied. The influence of the growing season and the time of soil salinization on salt tolerance as well as the tolerance during germination have also been investigated.

Under early salinization regimes and high evapotranspiration demands, yields were reduced by 50% of the maximum at EC_{se} of 6 mmhos/cm. This latter figure means an almost two-fold higher salt tolerance than that generally reported for Phaseolus sp. Furthermore, salt tolerance was increased by almost 100% when the crop was grown under low evapotranspiration demands (fall culture). An additional 30% salt tolerance increase was observed when soil salinization was delayed twenty days. Increasing yields of first picking and dry pod matter observed with increasing soil salinity suggest that soil salinity accelerates fruit ripening.

REFERENCES

Bernstein, L. 1963. Osmotic adjustment of plants to saline media. II. Dynamic phase. Amer. J. Bot., 50:360-370.

Bernstein, L. 1974. In J. van Schilfgaarde, ed., Drainage for Agriculture, Am. Soc. of Agron., No. 17, Madison, 700 pp.

Bernstein, L. and A. D. Ayers. 1951. Salt tolerance of six varieties of green beans. Proc. Am. Soc. Hort. Sci., 57:243-248.

Bernstein, L. and L. E. Francois. 1973. Leaching requirement studies: sensitivity of alfalfa to salinity of irrigation and drainage waters. Soil Sci. Soc. Amer. Proc., 37:931-943.

Bernstein, L. and G. A. Pearson. 1965. The influence of exchangeable sodium on the yield and chemical composition of plants. I. Green beans, garden beets, clover and alfalfa. Soil Sci., 82:247-258.

Brown, J. G. and R. K. Jackson. 1955. A note on the potentiometric determination of chloride. Proc. Amer. Soc. Hort. Sci., 65:187-190.

Gauch, H. G. and C. H. Wadleigh. 1942. The influence of saline substrates upon the absorption of nutrients by bean plants. Proc. Amer. Soc. Hort. Sci., 4:365-369.

Hoffman, G. J. and S. L. Rawlins. 1971. Growth and water potential of root crops as influenced by salinity and relative humidity. Agron. J., 63:877-880.

Hoffman, G. J., S. L. Rawlins, M. J. Garber, and E. M. Cullen. 1971. Water relations and growth of cotton as influenced by salinity and relative humidity. Agron. J., 63:820-822.

Jacoby, B. 1964. Function of bean roots and stems in sodium retention. Pl. Physiol., 39:445-449.

Kirkham, M. B., W. R. Gardner, and G. C. Groloff. 1969. Leaf water potential of differentially salinized plants. Pl. Physiol., 44:1378-1382.

Lunin, J., M. H. Gallatin, and A. R. Batchelder. 1961a. Effects of stage of growth at time of salinization on growth and chemical composition of beans: I. Total salinization accomplished in one irrigation. Soil Sci., 91:194-202.

Lunin, J., M. H. Gallatin, and A. R. Batchelder. 1961b. Effects of stage of growth at time of salinization on growth and chemical composition of beans: II. Salinization in one irrigation compared with gradual salinization. Soil Sci., 92:194-201.

Meiri, A. and Poljakoff-Mayber. 1970. Effect of time of exposure to salinity on growth, water status and salt accumulation in bean plants. Ann. Bot., 34:383-391.

Mendizábal, M. and G. Verdejo. 1968. A new way of culture to decrease salinity. In Hugo Boyko, ed., Saline irrigation for agriculture and forestry, 325 pp.

Millar, A. A. and W. R. Gardner. 1972. Effect of the soil and plant water potentials on the dry matter production of snap beans. Agron. J., 64:559-562.

Nieman, R. H. and L. L. Poulsen. 1967. Interactive effects of salinity and atmospheric humidity on the growth of bean and cotton plants. Bot. Gaz., 128:69-73.

Parra, M. A. and G. Cruz-Romero. 1976. On the dependence of salt tolerance of beans on soil water matric potentials. (Submitted to Plant and Soil).

Shalhevet, J. and L. Bernstein. 1967. Effect of vertically heterogeneous soil salinity on plant growth and water uptake. Soil Sci., 106:85-93.

Shalhevet, J., P. Reiniger, and D. Shimshi. 1969. Peanut response to uniform and non-uniform soil salinity. Agron. J., 61:384-387.

Ulrich, A. 1956. Plant analysis as a guide to fertilization of crops. Better Crop with Plant Food, 40 (6):6-10, 35-38.

USE OF HIGHLY-SALINE WATER IN CITRUS IRRIGATION

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INTRODUCTION

High Cl salinity in the ground water used for irrigating citrus orchards in the southern part of the Gaza coastal area has dictated cultural practice to citrus growers in this region. Farmers have learned to plant orchards with sour orange stocks, and to bud them to Valencia orange or grapefruit, both of which have been found to be more resistant to salinity than the Shamouti orange.

Irrigation is carried out in single-tree basins, with large applications of the highly-saline water (500-1500 ppm Cl) being given at relatively-short intervals (12-14 days). Such practice results in effective leaching of the root zone in the more permeable soils during the course of each irrigation, slowing the build-up of Cl ion concentration in the soil to levels which affect orchard performance slightly, if at all, during the early years of growth and cropping. However, it is common knowledge in the region that peak yields of saline-water irrigated orchards are lower than those grown with non-saline water, and that yields in these orchards begin to decline earlier, as well, reducing the long-term profitability.

Vegetative growth on trees in the saline-water region is less luxuriant, most of it flushing in the spring and early summer, when the relatively salt-free soil profile (leached by winter rains) and milder weather conditions are conductive to growth. Late summer and fall flushes are smaller in extent, and tend to become almost insignificant on older trees. The leaves become chlorotic, senesce and drop earlier, so that die-back of peripheral twigs is quite common in such orchards during the fall and winter months.

Profitability of the many Valencia orange orchards in the region is depressed still further in later years by a high incidence of creased fruit (Ericson, 1968) which become increasingly evident with the gradual reduction in the average size of the fruit as the trees reach mature bearing age.

In the course of an irrigation trial in a Valencia on sour orange grove irrigated with highly-saline water, various combinations of cultural and irrigation practices were tried with the aim of increasing the vigor of vegetative growth of the trees, on the one hand, and of reducing creasing of the fruit, on the other. Results of one such combination comprise the substance of this report.

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MATERIALS AND METHODS

The orchard used for the irrigation trial had been the locale of a previous investigation of various irrigation methods using highly-saline water, and has been described in a previous report (Goell et al., 1975). The irrigation trial, testing the frequency and the rate of application of irrigation, was begun in the spring of 1970, when the trees were 13-14 years old.

The well water used for irrigation contained 1,050 ppm Cl (total dissolved salts 4500 ppm), with E_c values of 4.22 mmhos/cm and Sodium Adsorption Ratio of 9.84. Such values are considered rather high for the irrigation of citrus in Israel, where the recommended limits for salinity in irrigation water are usually expressed as 250 cm Cl for orchards irrigated with low-volume, under-canopy rotational sprinklers.

Cultural practice was the same for the trial grove as for neighboring commercial orchards. The only difference introduced was the application every year of potassic fertilizer, both as KNO_3 sprays and as K_2SO_4 soil amendments, in an effort to reduce creasing of the Valencia oragnes. Check plots, without the K amendments, were located outside of the experimental block.

In the late spring of 1973, water supplies to the experimental grove were cut off for 21 days (May 29 - June 19), and after one uniform irrigation, for a further period of 35 days. When irrigation was finally resumed on July 24th, 500 gms of urea fertilizer were applied per tree with the first irrigation.

The growth response of the trees after irrigation was resumed was so remarkable that similar drought periods, brought about by the stoppage of irrigation, were initiated in 1974 and in 1975. The stoppage in 1974 consisted of two periods, mid-June to mid-July and most of the month of August, separated by irrigation. In 1975, the period was shorter and undivided (June).

Spring-flush non-fruiting terminals were marked on trees of the experimental replications in the early spring of each irrigation season. Of these, only terminals which did not flush again during the summer and fall served as source material for 4-7 successive samplings during the season, from May, when leaves were judged to have reached final size, to November, when irrigation was terminated with the beginning of the winter rains.

Each sample consisted of 6 whole branches, removed *in toto* from trees in each replication of the irrigation experiment.

Branch length and the number of nodes and leaves were determined. The values of the *Leaf Weight/Area Index* (LWAI) were determined from disks of known area taken from leaf laminae, oven dried, and weighed. Leaf Cl levels were determined in milled, dried leaf matter, using the method outlined by Cotlove et al. (1958).

Yields were harvested from six trees per replication. The fruits from each tree were weighed, counted, and a large representative sample was used in determining the size distribution and percent of creased fruit in each size range.

The overall response of the trees to the combination of a period of moisture stress in early summer and the later application of highly-available N fertilizer upon removal of the stress was so much greater than the treatment effects, that it was decided, for the purposes of this report, to neglect the treatment effects.

Therefore, it should be noted that all results presented are averaged for the 18 replications of the irrigation trial.

RESULTS AND DISCUSSION

Vegetative Growth and Cl Accumulation in Spring-flush Terminals

In the years preceeding the first stoppage of irrigation in 1973, vegetative growth on the Valencia trees in the experimental orchard was typified by a gradual decrease of growth vigor in succeeding flushes growing on the same branch throughout a season. This meant that a preponderant number of the more vigorous spring-flush terminals marked each spring for sampling purposes was found to originate from buds on wood which was more than one year old. The spring-on-spring terminals found during the marking were usually considered to be unrepresentative of the average level of growth vigor.

An example of such a situation is presented in Table 1.

Table 1. Some vegetative growth parameters from two groups of spring-flush terminals in spring 1972. Group 1 consists of spring 1972 terminals found growing on marked 1971 terminals. Group 2 represents the average terminals marked in the usual manner for 1972 sampling. Means for each group.

Parameter	Group 1	Group 2
Length of branch (mm)	30.1	88.2
Nodes per branch	4.5	7.1
Length of internode (mm)	6.3	13.8
Leaf/node ratio	0.52	0.86
Weight of leaf (mg)	117.7	210.8

The first group of branches in Table 1 had been found growing on spring-flush terminals marked in the spring of 1971 and left to grow until June 1972, when the first sampling took place. The second group was typical of the 1972 terminals marked in April of 1972 to serve for periodic sampling thru the 1972 season. Both were about 3 months old, with fully expanded leaves.

The branches sampled as "continued" growth on the marked 1971 terminals were obviously much less vigorous than those marked for the 1972 season, which, upon closer inspection, were found to be subtended by branches which were generally older than one year. The leaves on the first group of branches were fewer in number (per branch), smaller, and contained 0.180% of Cl (in dry matter) compared to 0.158% in the leaves from the second group. Previous investigation had shown that leaves rarely lasted more than two full seasons under the conditions of the orchard under discussion, so that the weaker branches of Group 1 were considered more likely to suffer complete defoliation and die back earlier than the more vigorous branches of the second group.

A number of vegetative growth parameters obtained from the periodic sampling of marked spring-flush terminals in the years 1972-1975 are presented in Table 2. The values in the table are averaged for all sampling dates for each year. Except for leaf dry weight, the parameters presented are of a type which achieved final dimensions during the period of growth in the spring, and have remained constant throughout the samplings.

Table 2. Vegetative growth parameters for spring-flush, non-fruiting terminals marked for periodic sampling in April of each season. Annual means.

Parameter	1972	1973	1974	1975
Branch length (mm)	92.2	89.5	102.2	86.0
Nodes per branch	6.9	6.7	6.6	6.3
Leaves per branch	6.1	5.7	5.4	5.5
Internode length (mm)	13.5	13.5	15.6	13.8
Leaf area (mm^2)	2178	2424	2615	2621
Leaf dry weight (mg)	211	219	229	236

The average lengths of the spring-flush terminals in 1972 and 1973, which may be said to have reached full proportions before any stoppage of irrigation was instigated, were quite similar, the small difference in length being attributed to the small difference in the number of nodes per branch. Leaf size, as exemplified by the weight or area, was greater in 1973 than in 1972.

By the time regular irrigation was resumed, in late July 1973, the small June flush had grown and matured. The flush which started in August was much stronger than in previous years; branches were more numerous, and leaves larger than any observed in the years since experimental work was begun in 1968 (Goell et al., 1975). The sampling of these branches, planned for the fall of 1973, did not take place due to circumstances beyond our control. However, the visual effect in late summer and fall of that year was one of a much younger orchard in full flush. The numerous branches were evenly distributed all around the tree canopy; leaves were large and dark in color, so that the total effect was one of great vegetative vigor, similar to that of a tree much younger and growing under ideal conditions. Vigorous growth continued on the trees right into late fall of 1973.

The effect of the vigorous late growth in 1973 was carried over into 1974. This could be seen in the greater vigor of the 1974 spring-flush branches, which were significantly longer than 1973 equivalents, had longer internodes and larger leaves than any previous spring flushes. The greater length of the 1974 terminals was mostly attributable to greater internode length, since the number of nodes did not change appreciably (Table 2).

Despite the fact that the irrigation stoppage treatment was repeated in summer of 1974, length of the spring-flush terminals, as well as internode length, dropped to 1973 levels again in the spring of 1975, together with a further drop in the number of nodes per branch. The reason for this reduction in growth per terminal, seems to have been the result of a greater number of vegetative terminals per tree, so that the total flush per tree was not reduced, but the average marked branch was.

Leaves were larger in spring 1973, compared with 1972, as a result of the greater reduction in the number of leaves than in the number of nodes per branch. Such a change in the leaf/node ratio (from 0.88 to 0.85) may be construed as a drop in leaf density on the average branch, giving rise to a larger individual leaf through the reduction of competition for leaf laminar expansion factors in the spring flush. The same may be said concerning the further drop in the leaf/node ratio in spring of 1974 (to 0.82). Leaf density on 1974 branches was further reduced by the greater internodal length (Table 2), so that leaves were larger still in spring 1974 than in the previous years. Since the greater internode length is considered to be an indication of greater vegetative growth vigor (Goell, 1964), such greater vigor may be included among the factors responsible for the greater leaf size on spring 1974 terminals.

Leaf size in spring 1975 remained at 1974 levels, in spite of the general reduction in growth of the spring-flush terminals upon which they grow. One might have expected leaf size to be reduced in 1975, considering that the leaf/node ratio had risen to 0.88 on these branches, and that this, coupled with the shorter internodal length, brought about a considerable increase in leaf density, as defined above. The fact that leaf size was not reduced by the increase in leaf density moves us to conclude that its effects were countered by a general improvement in the conditions for leaf laminar expansion in spring 1975, reflecting the generally-improved vegetative status of the trees, built up during the previous two seasons.

Average leaf dry weight on the spring-flush terminals rose from year to year during the period 1972-5 (Table 2). Upon examination of leaf weights through the various samplings made during the irrigation season, it was noted that leaf dry weight reached peak levels in the September sampling in 1972 (220 mg/leaf). The same weight per leaf was reached in August 1973 in leaves which continued accumulating dry matter until peak values of 235 mg/leaf were reached in October 1973.

Peak dry weights of leaves were even higher in 1974 (250 mg/leaf in Nov.) and these remained high in 1975 as well - 248 mg/leaf being the value reached in the end-of-June sampling.

Production of dry matter continues in the leaf during its entire photosynthetic existence, but its accumulation in the leaf itself is limited mostly to the early period of leaf expansion, and to a lesser extent, to the period of growth and maturation of leaf laminar palisade and mesophyll layers (Steer, 1971). Thus, the major part of leaf dry matter accumulation takes place in a relatively short period, the rest being a very slow, and not easily perceptible process which continues for a much longer part of the leaf's total existance. Since leaf laminar area attains its final size in the first part of this period (Steer, 1971), we felt that measuring the leaf laminar dry weight per unit area, as expressed by the Leaf Weight/Area Index, (LWAI) might serve as indication of the changes taking place in the total weight of the leaf, as well. The results of periodic samplings of the spring-flush leaves are presented in Figure 1.

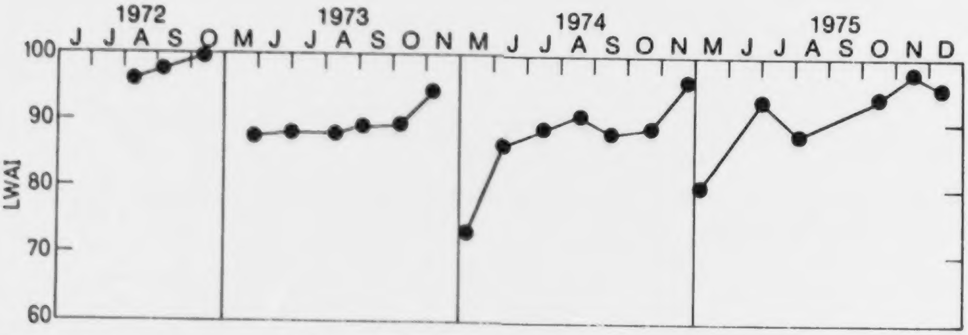

Figure 1. Changes in the Leaf Weight/Area Index (LWAI) values obtained from the laminae of spring-flush terminal leaves during the irrigation seasons 1972-1975.

The results presented are average values for all leaves sampled at any date. It may be seen that leaves had reached a more-or-less steady level of LWAI values by the end of May, while only the earliest samplings in 1974 and 1975 showed the significantly lower LWAI values typical for leaves which had not completed maturation of the palisade and mesophyll layers. Once leaves had achieved final development, changes in LWAI were minimal, until the end of October or beginning of November, when a significant rise in LWAI values was found in the 1973, 1974 and 1975 leaves. Such a rise seems to indicate a definite change in the ratio between photosynthate production and its disappearance from the leaf in the respiratory process as well as in translocation. A rise in this rate would indicate accumulation in the leaf laminar tissue, as evidenced by the rise in LWAI values.

In Figure 2, percent Cl in dry matter levels in the same spring-flush leaf samples are presented for 3 of the 4 seasons under review. Cl levels in the leaves rose rapidly in the spring and early summer of the seasons for which the results are available. However, while these continued to rise in the September and October samplings of 1972, they tended to decline during the late summer and fall samplings in 1973 and 1974. This drop in percent Cl corresponded to a tendency for increase in LWAI values in these leaves, seemingly as a result of the increase in vegetative vigor in the latter part of the growing season evinced by the trees in those years. It may be argued that the increase in vigor, as expressed by the large number of late-summer and fall flush leaves, might have acted to dilute the total amount of Cl taken up by the trees, by causing it to be distributed among a significantly larger number of sinks than in 1972. Such a hypothesis is supported by the fact the percent Cl levels were generally lower in 1973 leaves than in 1972, and that they dropped even more, on the average, in 1974 leaves, while water salinity levels and the irrigation regimes remained the same throughout the three seasons.

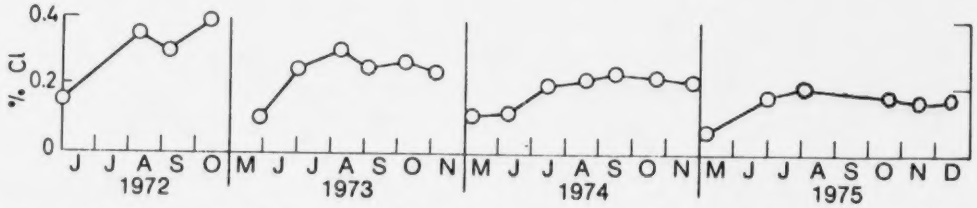

Figure 2. Changes in % Cl in the dry matter of leaves from spring-flush terminals during the irrigation seasons 1972-1975.

YIELDS

Yield parameters are presented in Table 3. Yields for the years 1970 and 1971 were included in the table, in order to give as full a picture as possible of the variability of the yields with the years. This is very important in a tree crop trial, where the changes in yield from year to year must be weighed on the basis of numerous carry-over effects - at least in the context of year-by-year analysis.

Yields of Valencia orange trees are subject to a certain degree of alternate bearing (Hilgeman and Sharp, 1970). The figures in table 3 bear this out: 1972 and 1974 are definite high-yield, or "on" years, while 1971 and 1973 may be classed as low-yield, or "off" years. The average size of the fruit may be affected by the number of fruit per tree, or more correctly, by the number of fruits per unit of bearing canopy in the tree. The latter parameter has not been calculated with any degree of exactitude for the trees in question, so suffice it to say that in Table 3, a rough relationship may be seen to exist between the number of fruit per tree and the average fresh weight of the fruit.

Table 3. Yield parameters for the years 1970-1975 for the trees of the irrigation experiment.

	Fruit No. per tree	Fresh Wt. Fruit (gms)	% creased fruit	Packed Yield 1/ (carton/dunam)	Gross Yield 1/ (tons/dunam)
1970	466	167	11.8	118	3.5
1971	346	180	18.3	90	2.8
1972	643	162	42.0	124	4.8
1973	366	199	8.3	118	3.3
1974	865	137	24.0	173	5.4
1975	588	175	18.9	169	4.7

1/ Tonnage and packed yield calculated on the basis of 46.2 trees to the dunam = 1000 m^2. Packed yield calculated after creased fruit was removed.

Profitability of the Valencia grove is best reflected by the packed yield. This parameter is dependent upon the combined effects of 1) the number of fruit borne per tree, 2) the size distribution of the fruit, and, 3) the percentage of the fruit rejected as unfit to be packed because of creasing.

Examination of the 6-year bearing record in Table 3 showed that the changes in the number of fruit per tree from year to year were not usually reflected in the packed yield. On the contrary, the contributory consequences of the changes in fruit size, and especially, in percentage creasing were effective in counterbalancing possible changes in profitability which might have been expected to result from changes in the fruit number in any particular year.

A good example of the above may be seen when 1972 and 1973 are compared.

The number of fruits per tree in 1972 was almost double that of 1973, but the combined effects of smaller fruit and very much higher percentage creasing in 1972 caused the packed yield for the two years to be almost equal.

Comparison of the very similar packed yields for 1974 and 1975 showed that they were obtained from yields which differed greatly in the number of fruit per tree as well as in the average weight of the fruit, while the differences were smaller in percentage creasing.

The differences, if any, in yield brought about by the increase in vegetative vigor of the trees from late 1973 and on are very difficult to assess on the basis of the 2 crop years whose results are available up to now. It can be stated that yields - both the number of fruit per tree and the packed yield - have been higher in the 1974 and 1975 crop years than in any of the previous years. It is further noteworthy that even the relatively very low number of fruits borne by the trees in 1973 produced a pack equal to that obtained from the much higher number of fruits borne by the same trees in the previous season. The reasons for this were the combined effects of a larger size of fruit and a great reduction in creasing in 1973. These two factors have been found to be related in many instances of work with Valencia oranges, as Cohen(1975) found in his work with isolated branches. This was also very often the case in our work, when the percentage of creased fruit was almost invariably found to rise in the smaller sizes of the fruit. Such a correlation is not so clearly marked when the average values for percentage creasing are plotted against average fresh weight values from Table 3. The results for 1972 obviously do not conform to the general trend, possibly because factors conducive to creasing were much more generally active on all fruit sizes in that year.

CONCLUSIONS

In reviewing the variation with the years of the growth response to the moisture stress - fertilizer treatment, it seems to us that the timing of this practice is of the utmost importance. Since our purpose was the stimulation of vegetative growth, especially of the summer flushes, this might mean the enhancement of the number of buds making growth in any one flush, as well as the stimulation of growth vigor of the individual branches involved.

In 1973, the period of relative moisture stress overlapped the period when the early summer flush usually grows. This flush seems to have depressed, or at least largely delayed until the stress was removed, in mid-July. By then, many more buds than usual were ready to burst into growth, and the application of water, together with a highly-available nitrogenous fertilizer, did encourage the great burst of vegetative growth described above. Such growth may have been further enhanced by the small number of fruits borne on the trees in 1973.

The second and third year of application of the stress-fertilizer treatment to the trees have not evoked a growth response of similar proportions. Possible reasons for this may well include an upset of the physiological timing of the treatment, due to the basic changes wrought in the trees by the 1973 response. The heavier yields of the 1974 and 1975 seasons may have had a contributory effect on the low level of reponse, as well.

A trial based on the above considerations is now in the planning stage. Small observation plots are also being sought out in Valenica orange groves irrigated with very saline water. These will serve the further investigation of the timing and duration of the first-year response to the treatment, as a method for rejuvenating groves which are aging too early as a result of high salinity.

LITERATURE CITED

Cohen, A. 1975. Personal Communication.

Cotlove, E., H.V. Trantham and R.L. Brown. 1958. An instrument for and method for automatic, rapid and accurate titration of Cl in biological samples. J. Lab. Clin. Med. 50:358-371.

Ericson, L.C. 1968. General physiology of citrus. In W. Reuther, ed., (2nd edition), Citrus Industry, University of California Press.

Goell, A. 1964. Vegetative growth of citrus branches. Some morphological and physiological aspects. M.Sc. Thesis, presented to the Faculty of Agriculture, Hebrew University. (In Hebrew).

Goell, A., M. E-Rais, A. El-Wahidi, and Y. Bar. 1975. Irrigation of Valencia orange trees in the Gaza Strip with water of very high salinity. Proc. Int. Symp. on the Use of Brackish Water in Development, Beer Sheba, Israel. (In press).

Hilgeman, R.H., and F.O. Sharp. 1970. Response of Valencia orange trees to four soil-water schedules during 20 years. J. Am. Soc. Hort. Sci. 95:739-748.

Steer, B.T. 1971. The dynamics of leaf growth and photosynthetic capacity of Capsicum frutescens L. Ann. Bot. 35:1003-1015.

PROBLEMS IN PREDICTING AND MEASURING SOLUTE CONCENTRATIONS IN IRRIGATED FIELDS

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INTRODUCTION

Presently around the world there are several large experiments underway studying the use of irrigation management for salinity control.

Our experiment at UC Riverside is looking into the feasibility of using highly saline irrigation waters for crop production. Successful management of this approach will require two conditions to be met: use of high frequency irrigation to maintain the water potential of the root zone at a high enough level for crop use, and maintenance of a positive excess of application over evapotranspiration, expressed as a leaching fraction, to prevent an accumulation of salts within the root zone. Furthermore, to minimize salt loading of groundwater reservoirs and to encourage salt precipitation, it is desirable to keep the leaching fraction as small as possible.

Because of highly variable evapotranspiration, maintaining a constant leaching fraction requires adjusting irrigation levels in response to feedback from soil or environmental sensors. This paper will address itself to the problems associated with using feedback from soil salinity sensors and will present experimental measurements and model calculations illustrating the major causes of spatial variability of these sensors.

EXPERIMENTAL DESCRIPTION

The experimental site was located on the campus of the University of California, Riverside. Twenty-four lysimeters of 1.1 m^2 surface area and 1.5 m depth contained six replicates of four soil types (Altamont clay loam, San Emigdio sandy loam, Greenfield sand, Holtville clay loam). These lysimeters were filled with topsoil in 1957 and have been in continuous use since that time. Their soil structure and bulk density distribution are now typical of field profiles. Each lysimeter rests on a pea gravel envelope from which drainage is collected by an implanted hose. Salinity sensors and tensiometers (also used to extract solution) were installed at five vertical depths (5, 20, 50, 80, 120 cm) and replicated up to three times in the high salinity treatments. Neutron tubes were placed at the center of each lysimeter and water content readings taken periodically at four depths (20, 50, 80, 120 cm).

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In a preliminary experiment, nine of the lysimeters were wet from below to saturation, covered and allowed to drain. Tensiometer readings and neutron probe values were taken at subsequent intervals and the water transport characteristics determined by the instantaneous profile method (Rose et al., 1965). These characteristics exhibit considerable scatter but no statistically-significant differences were found between different horizons or between different lysimeters of the same soil type.

Table 1. Chemical Composition of irrigation waters.

Salt level	Concentration (meq/l) Cl^-	HCO_3^-	$SO_4^=$	Ca^{++}	Mg^{++}	Na^+	Electrical conductivity (mmhos/cm)
tap water	0.5	2.5	1.25	2.7	0.9	1.6	0.6
low	6.2	3.8	13.2	7.6	2.9	12.3	2.2
medium	12.8	4.6	30.9	13.0	6.6	25.3	3.9
high	28.2	5.8	64.5	24.5	16.5	47.8	7.1

On January 31 (subsequently referred to as day zero), an experiment was initiated to study the influence of high-frequency irrigation at low leaching fractions on crop response to high salinity irrigation waters. Three levels of irrigation water salinity, synthesized as multiples of Colorado River water, were used as inputs to the lysimeter (Table 1). Initially, all lysimeters were ponded twice with 2 cm of salt solution. In order to maintain low salt concentrations in the seed bed, all lysimeters were irrigated with 2.3 cm of tap water during day four. On day six, winter wheat (_Triticum aestivum_, var. _Cahemi 71_) was planted in all lysimeters. In addition, on day 25, 5 cm of rainwater entered the lysimeters. Other than these inputs, all lysimeter irrigations consisted of saline water at one of three levels (EC = 7.1, 3.9, 2.2 mmho/cm). Irrigation was first maintained by automatic drip emitters, but following clogging due to salt precipitation, water was applied manually over the surface which had been worked into a loose, granular state in the top 10 cm.

EXPERIMENTAL RESULTS

Figure 1 shows the relationship between hydraulic conductivity and water content determined for the lysimeters containing Altamont clay loam. The large scatter in point measurements is typical of field determinations and reflects errors due to sensor interpolations, nonuniform infiltration, and lateral variations in transport. The envelope of these points may be thought of as confidence limits for the relationship.

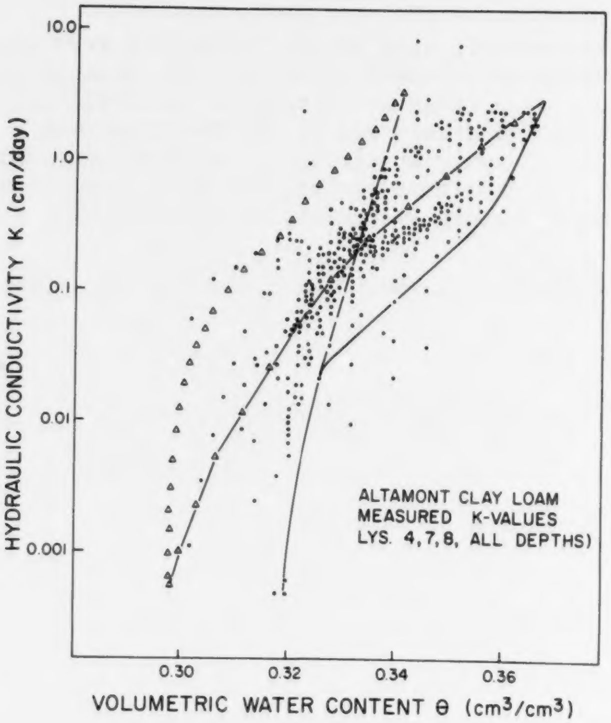


Figure 1

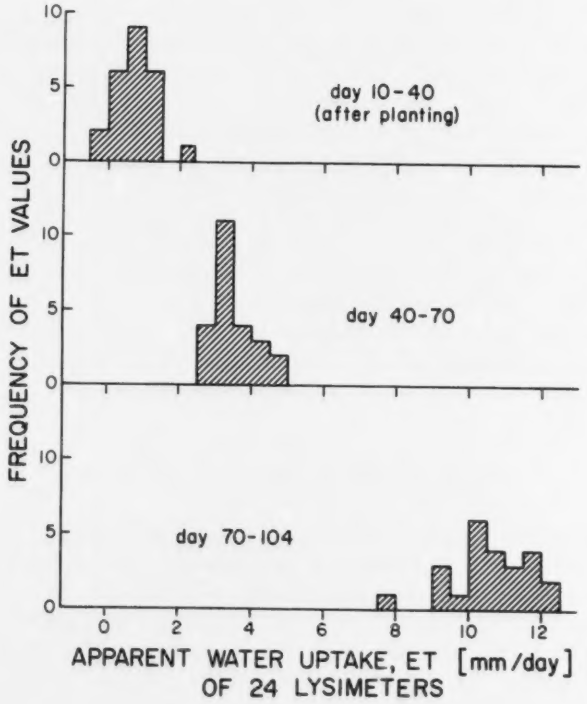
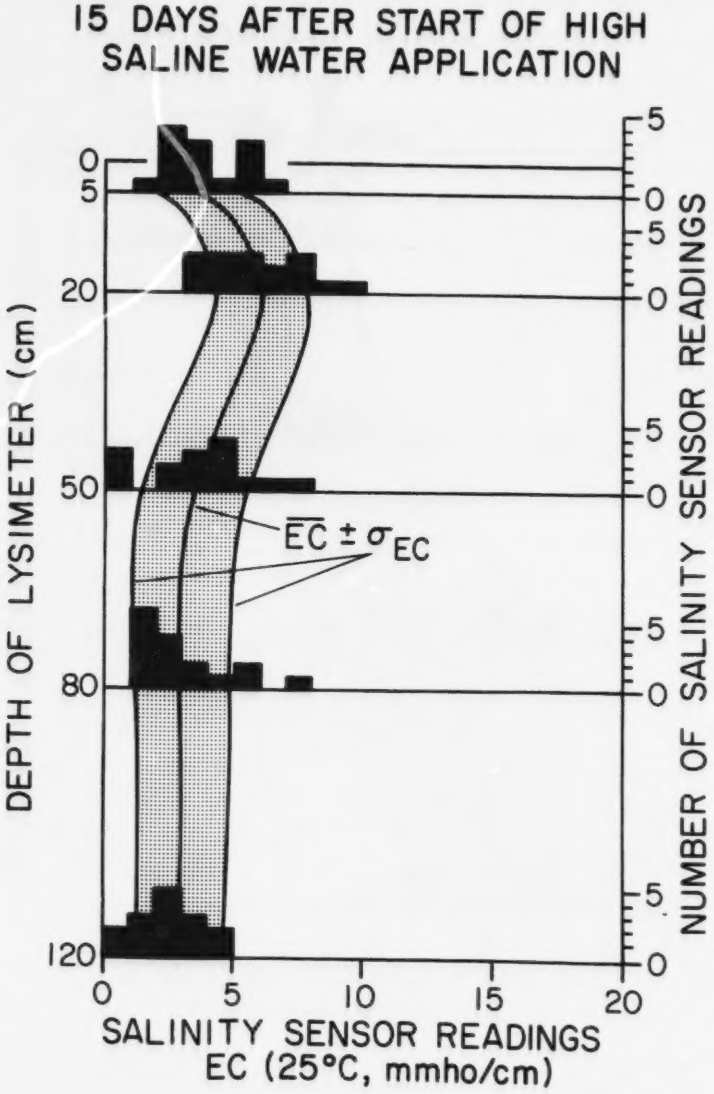
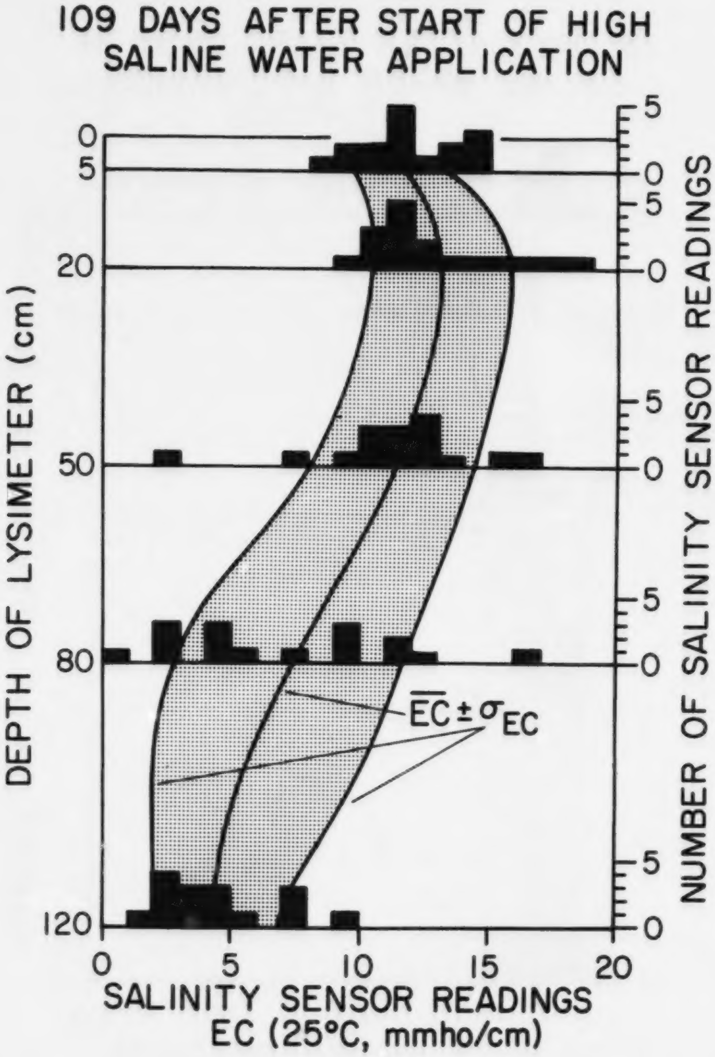


Figure 2



15 DAYS AFTER START OF HIGH SALINE WATER APPLICATION
DEPTH OF LYSIMETER (cm)
0
5
20
50
80
120
NUMBER OF SALINITY SENSOR READINGS
5
0
5
0
5
0
5
0
5
0
$\overline{EC} \pm \sigma_{EC}$
0
5
10
15
20
SALINITY SENSOR READINGS
EC (25°C, mmho/cm)

Figure 3


109 DAYS AFTER START OF HIGH SALINE WATER APPLICATION
DEPTH OF LYSIMETER (cm)
0
5
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80
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NUMBER OF SALINITY SENSOR READINGS
5
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5
0
$\overline{EC} \pm \sigma_{EC}$
0
5
10
15
20
SALINITY SENSOR READINGS
EC (25°C, mmho/cm)

Figure 4

Table 2. Hydrologic Balance for Wheat Experiment

1 February to 4 June

Lysimeter Soil	No.	Irrigation Salinity Level	Irrigation	Drainage	Storage Change	ET
			cm	cm	cm	cm
Holtville cl	1	high	79.7	2.7	2.1	74.9
	10	high	75.9	1.6	1.3	73.0
	6	med	75.0	1.5	5.0	68.5
	26	low	72.4	2.9	1.1	68.4
Greenfield s	2	high	71.2	0.0	7.3	63.9
	11	high	74.9	0.3	8.8	65.8
	12	med	76.2	0.8	7.3	68.1
	17	low	77.8	0.0	7.8	70.0
Altamont cl	4	high	77.1	0.8	5.5	70.8
	8	high	76.6	0.2	2.7	73.7
	7	med	75.0	1.5	2.7	70.8
	18	low	80.1	0.0	3.7	76.4
San Emigdio sl	5	high	77.0	2.7	6.0	68.2
	9	high	74.8	2.8	7.0	65.0
	14	med	73.1	2.7	4.9	65.6
	25	low	73.9	3.6	3.9	66.5
					Average ET	69.4
					Std. Dev.	3.6

Figure 2 shows the evapotranspiration ET from the lysimeters determined from a hydrological balance over several weeks for the lysimeters, expressed as a frequency diagram. This diagram may be viewed as a distribution of point measurements of ET across the experimental site.

Figures 3 and 4 illustrate the distribution of electrical conductivity EC readings at a given depth at two times (15 and 109 days) for all of the high salinity irrigation lysimeters expressed as a frequency diagram. The large scatter in concentration values raises serious questions both about the major physical influences on this distribution and about the problems faced in using these readings to guide irrigation management. These points are discussed in further detail below.

Final Experimental Balances

Table 2 shows the final hydrologic balances for the entire 125 day wheat experiment. The main features of interest are the increase in storage of all lysimeters due to a highly depleted initial state, the small volume of drainage past 150 cm, and the similar final ET losses. The coarse textured soils had a somewhat lower ET over the period of the experiment, probably due to greater stress within the root zone.

Table 3 shows the final salt balance for the experiment. The last column represents the amount of precipitation occurring during the trials, expressed as the difference between salt input, output, and storage increase. With the exception of one lysimeter, this total was positive.

Table 4 shows the final wheat dry matter and grain yields obtained in the trials. There were no significant differences between treatments, reflecting both the high salt tolerance of the Cahemi 71 variety and the low salinity of the soil water at the beginning of the experiment. Future experiments should begin to reflect differences now that the profile is salinized.

THEORY

High speed digital computers have made it possible in principle to numerically solve the exact nonlinear flow equation for water and salt transport through a porous media; however, the absence of detailed experimental calibrations needed as input to the equations along with the expense of running simulations over long periods of time have made it necessary to construct approximate field-oriented models of the transport process wherever possible.

Water Model

The water model we are using in this investigation is an extension of an earlier gravity flow system (Jury et al., 1976) which uses the following assumptions: 1) the soil profile is divided into six layers, 2) water movement is assumed to be downward and to occur at a rate characteristic of the value of the soil capillary conductivity associated with the water content of the overlying layer at any given time, 3) the fraction of the total water uptake extracted from a given layer is a function only of depth, 4) the total daily evapotranspiration and irrigation are the values measured in the experiment.

Under these assumptions, the equations to be solved for each layer are

$$L \frac{d\theta_j}{dt} = K(\theta_{j-1}) - K(\theta_j) - S_j \qquad j = 1,2,\ldots 6 \tag{1}$$

where L is the thickness of the layer (here 20 cm), $K(\theta_j)$ is the soil water conductivity, S_j is the fraction of the evapotranspiration extracted from layer j.

Table 3.

SALT BALANCE FOR WHEAT EXPERIMENT

1 February to 4 June

Lysimeter Soil	No.	Soil Initial	Soil Final	Salt Input	Salt Output	Salt Balance
		----------(mmho/cm)	x	(liters)----------		
Holtville cl	1	707	3944	5917	92	2588
	10	729	3060	5604	35	3238
	6	671	3030	3043	62	622
	26	680	1267	1564	75	902
Greenfield s	2	559	3524	5232	0	2267
	11	346	2945	5523	4	2920
	12	461	1966	3200	13	1682
	17	332	1110	1692	0	914
Altamont cl	4	773	5923	5707	19	538
	8	745	3545	5670	4	2866
	7	829	4598	3143	25	-651
	18	611	1480	1748	0	879
San Emigdio sl	5	362	3594	5700	54	2414
	9	686	2948	5519	59	3198
	14	540	1873	3056	92	1631
	25	542	874	1600	56	1212

Table 4. Grain and dry matter yields by lysimeter

Lysimeter No.	Soil type[+]	Total Dry matter (gm/lys.)	Grain yield (gm/lys.)	Grain weight (gm/1000 seeds)
		High salinity irrigation		
1	Hcl	1028	1068	32.5
10	Hcl	1116	1094	32.4
4	Acl	961	1024	32.1
8	Acl	1271	1017	31.9
2	Gs	727	939	32.5
11	Gs	620	824	32.2
5	SEsl	783	1084	33.0
9	SEsl	544	1025	33.4
		Medium salinity irrigation		
6	Hcl	750	981	33.3
16	Hcl	867	1039	32.6
7	Acl	1110	959	29.7
23	Acl	915	1042	33.9
12	Gs	831	875	30.8
15	Gs	783	947	32.3
14	SEsl	692	916	34.0
24	SEsl	788	968	37.0
		Low salinity irrigation		
19	Hcl	906	964	33.2
26	Hcl	967	948	32.0
18	Acl	1061	1084	34.0
28	Acl	941	859	30.3
17	Gs	819	967	34.4
27	Gs	843	926	32.1
21	SEsl	830	862	30.8
25	SEsl	890	904	34.4

[+] Hcl - Holtville clay loam; Acl - Altamont clay loam; Gs - Greenfield sand; SEsl - San Emigdio sandy loam

The assumptions made in constructing this model are specific to our experimental system. Continuous irrigation in excess of atmospheric demand results in downward flow through the profile so that the gravity flux assumption is a reasonable representation. We also made a comparison of our model with a finite difference solution of the exact differential equation over a 40-day trial period and found good agreement with calculated water fluxes as a function of depth and reasonable correspondence with water content predictions. A further test of the gravity flow assumption is found by looking at a calculation of steady downward flow with water uptake expressed as an exponentially-decreasing function of depth. The equation and surface boundary condition are:

$$\frac{d}{dz}\left[-K(h)\left(\frac{dh}{dz}+1\right)\right] + S(z) = 0 \qquad (2)$$

$$-K(h)\left(\frac{dh}{dz}+1\right) = -F \qquad z = 0 \qquad (3)$$

where h is the soil water head, F is the amount of water applied and S(z) is the water uptake function which satisfies

$$\int_{-L}^{0} S(z)dz = ET \qquad (4)$$

with L the depth of the root zone. For simplicity, we assume the form

$$S(z) = A \exp(Bz) \qquad (5)$$

Figure 5 is a plot of the ratio of the gravitational component of downward flow K(h) to the total downward flow K(h) (dh/dz + 1) as a function of depth for various leaching fractions LF = 1 - ET/F, using an exponential approximation $K(h) = \alpha \exp(B h)$ to the measured data for the Altamont soil. It is seen that only at extremely small leaching fractions do sufficient feed gradients develop to make the gravity flow assumption unreasonable. For our system with leaching fractions above .05 the effect of the gravity flow model is to associate a slightly different water content profile with a downward flux profile than would a complete numerical solution of the Richards Equation.

Salt Model

The output of the water model is a representation of the water flux K(z,t) and water content θ(z,t). This is used as an input to the salt flow equation (Gardner, 1965).

$$\frac{\partial(C\theta)}{\partial t} = \frac{\partial}{\partial z}\left(D\theta\frac{\partial C}{\partial z}\right) - \frac{\partial}{\partial z}(J_w C) \qquad (6)$$

where C is the solution concentration, J_w is the soil water flux, and D is the effective dispersion coefficient which for the range of small

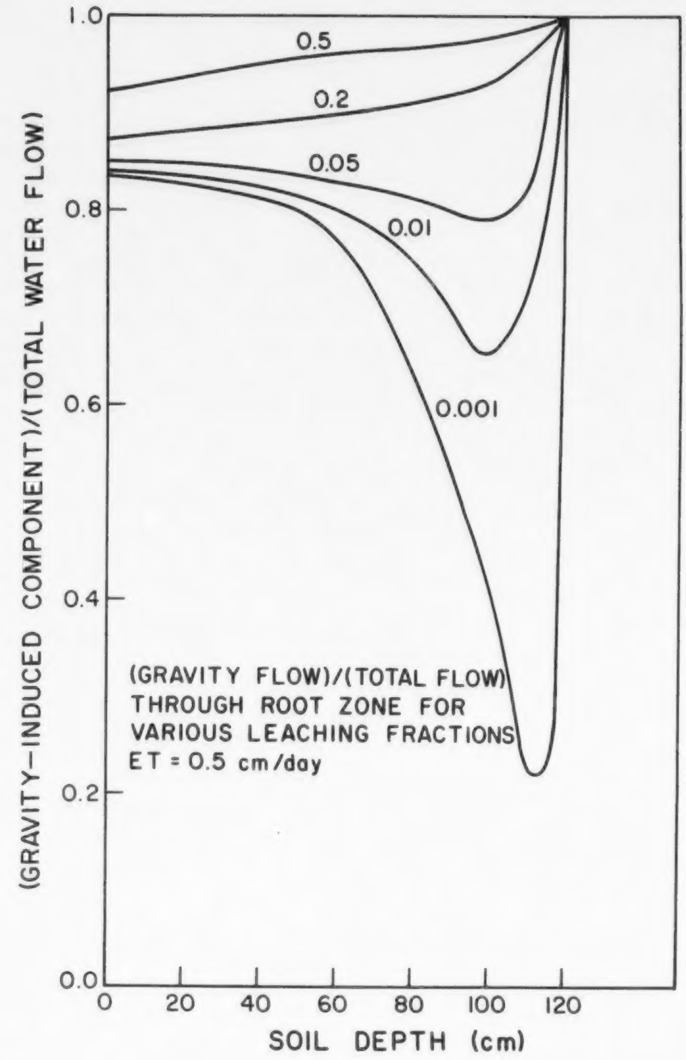


Figure 5

water fluxes encountered in this experiment was given the value of 1 cm^2/day.

Equation (1) was solved by Runge-Kutta integration with iteration and a variable time step. Equation (6) was solved by explicit finite differencing using a space step of 10 cm and a time step of 1 day. The calculations were performed on the IBM 360/50 computer, requiring approximately 30 sec of computer time and a cost of $1 per 100 days of output. Water and salt balances were in error by less than 0.5% after 100 days.

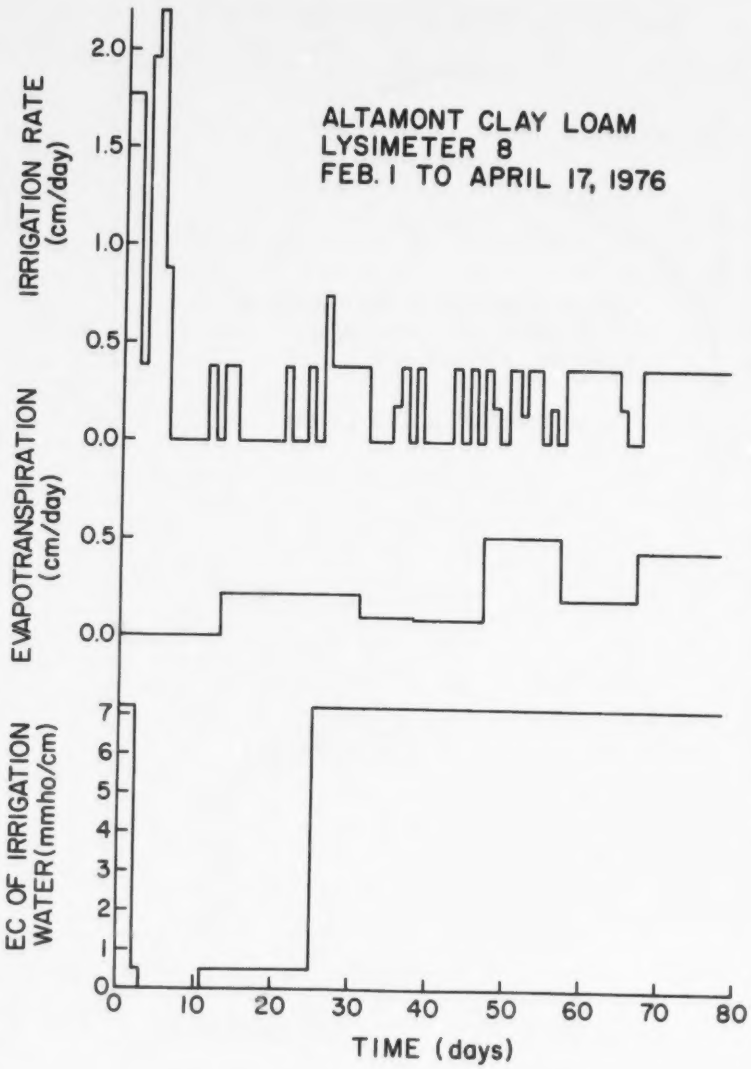


Figure 6

SIMULATION RESULTS

The simulations were designed to test the effect of varying different physical parameters within the range of their experimental confidence limits and to determine the resulting variations in solute concentration. For the conductivity-water content relationship these limits are defined by the point spread in Fig. 1. Water inputs were assumed to be bounded by a ±10% uncertainty. Water uptake was assumed to occur within 60 cm of the surface, the lowest observed depth of extraction during the first 75 days. Each simulation used the experimentally-measured inputs shown in Fig. 6.

The first simulation was run for 75 days using an exponential water uptake pattern (65%, 25%, 10% in the top three layers), but employing each of the four limiting capillary conductivity-water content curves shown in Fig. 1. The predicted water content and salinity profiles for each simulation are shown in Fig. 7.

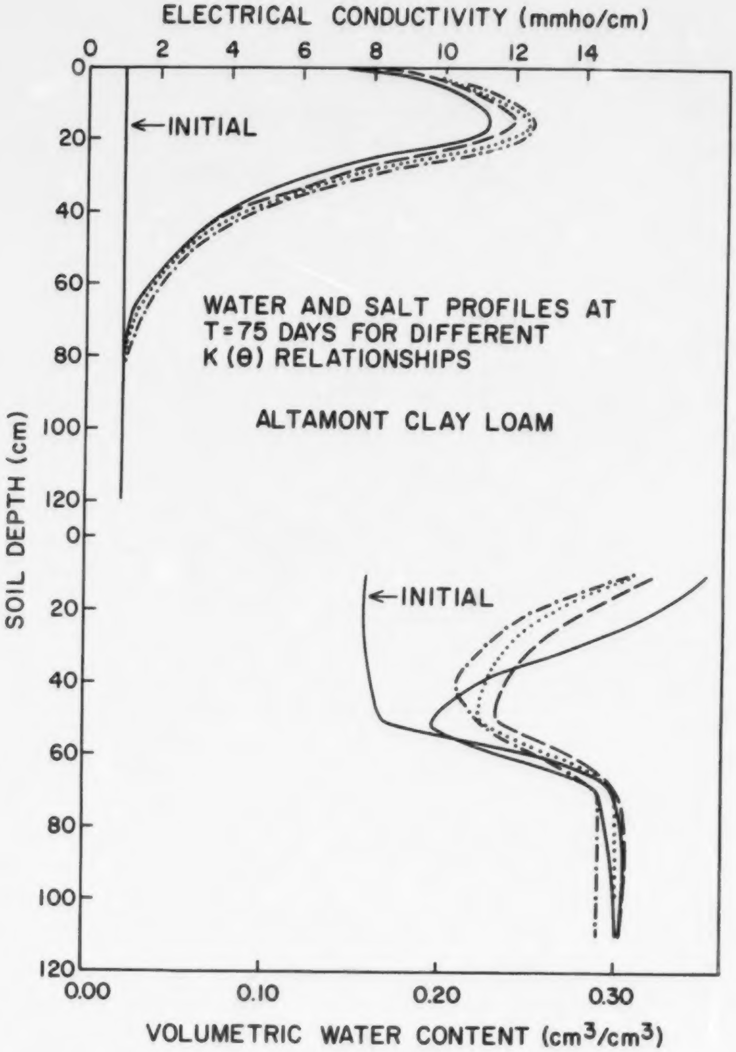


Figure 7

The second simulation was run for 75 days using the central conductivity curve, an exponential water uptake pattern, but for water inputs of 0.9, 1.0, and 1.1 times the daily irrigation amounts shown in Fig. 6. The water content and salinity profiles for this calculation are shown in Fig. 8.

The third simulation was run for 75 days using the central conductivity curve and the inputs shown in Fig. 5, but for different assumed uptake distributions within the top 60 cm divided into uniform regions of 20 cm each, corresponding to the top three soil layers in the water model. The results of this simulation are shown in Fig. 9.

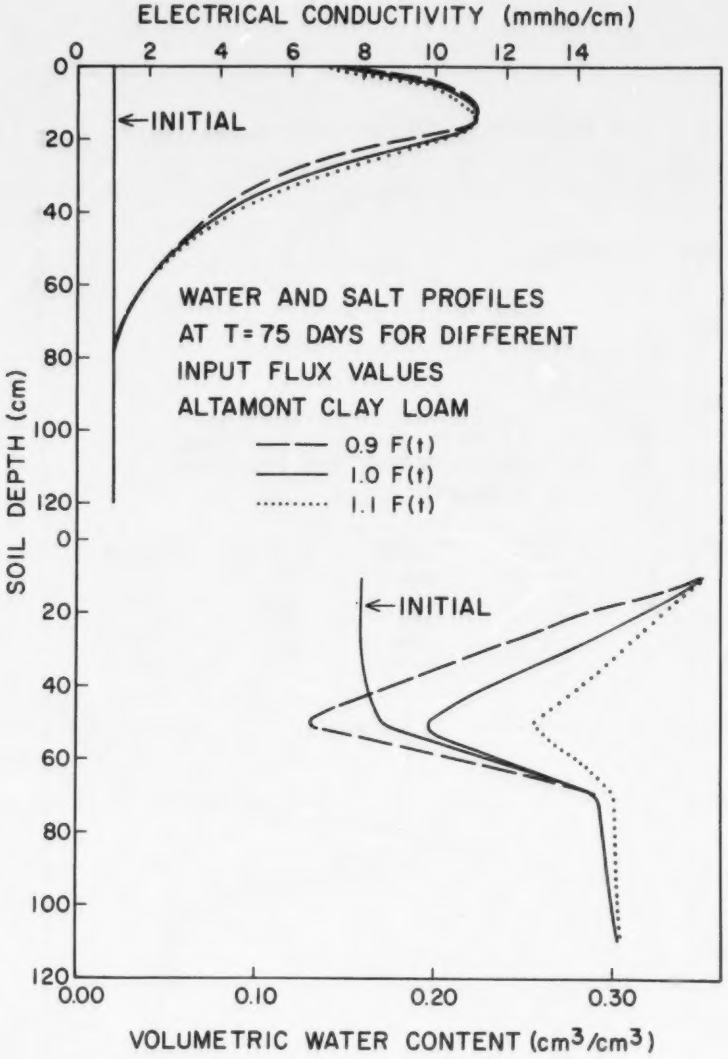


Figure 8

DISCUSSION

It is clear that among the possibilities considered, the only physical characteristic having a pronounced influence on solute concentration is the relative water uptake distribution. Conductivity variations have little effect on material transport in this system because the control for water and salt movement is exerted at the inflow boundary. In all cases the soil water content adjusts to the value characteristic of the water flux at that point in the profile, as seen by the relatively large variation in soil water content with depth at 75 days. Even for the large range of conductivity relations chosen, however, this water content distribution is not great enough to have much influence on the solute concentrations.

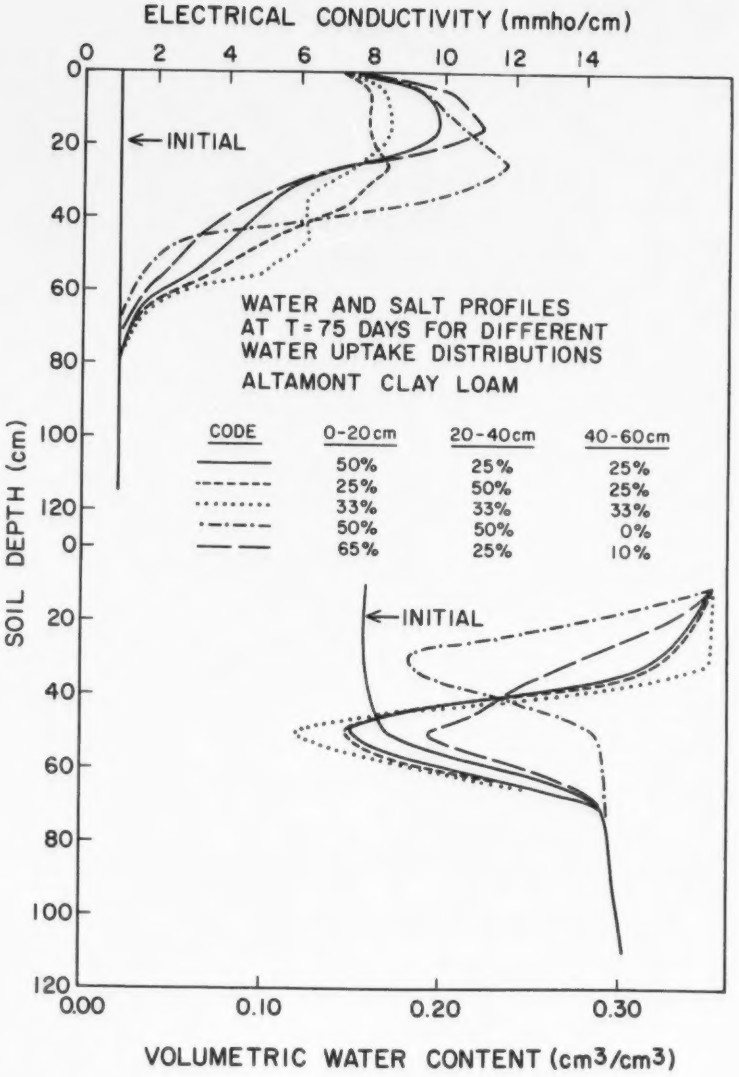


Figure 9

The small variations in solute concentrations in the second case, using input fluctuations, is due to compensating effects. The mass of salt input varies by ±10%, but so does the volume of water. Associated with higher salt inputs are larger water volumes, so that the concentration or salt mass per solution volume tends to remain the same in all cases. This correspondence is due in part to the low initial water content of the lysimeter which tended to maximize final differences in water storage among the three cases.

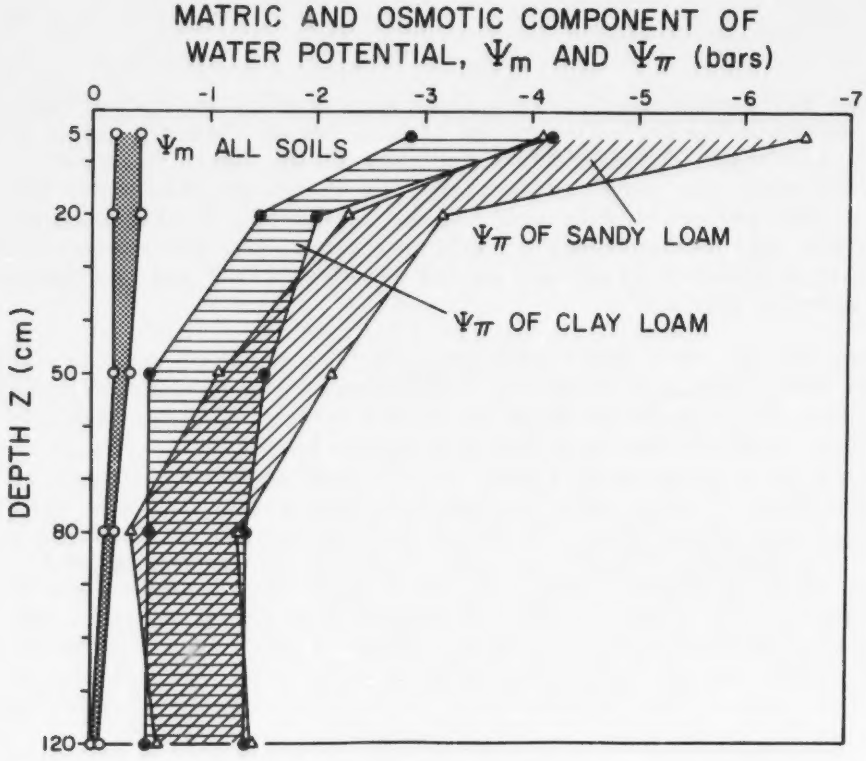
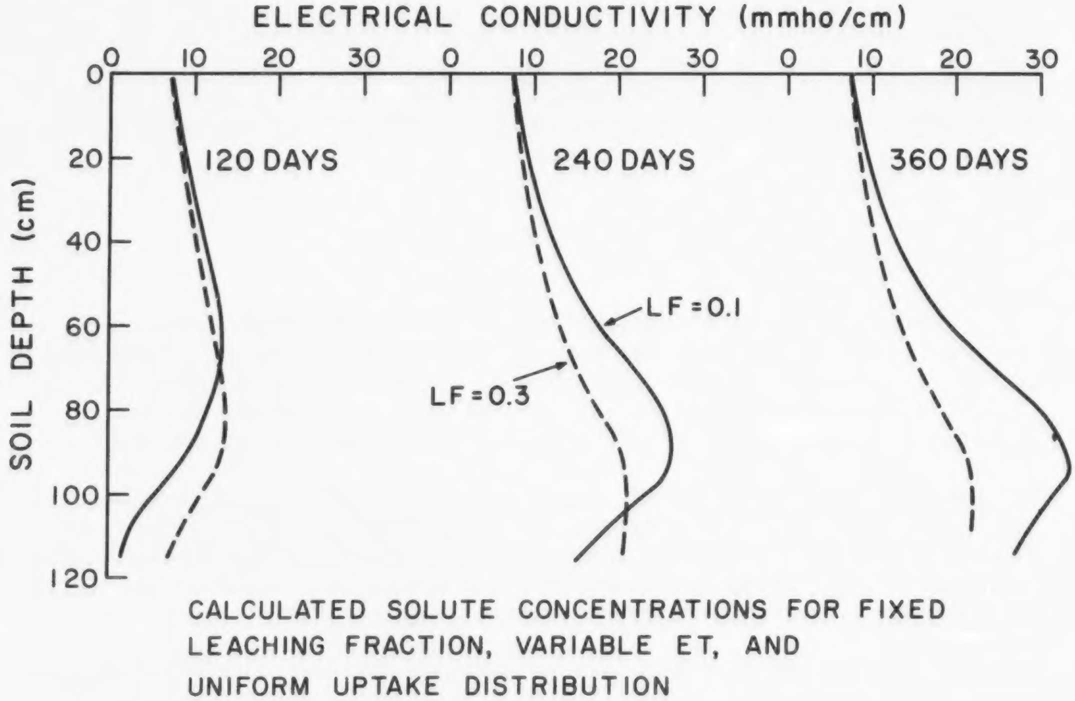


Figure 10



CALCULATED SOLUTE CONCENTRATIONS FOR FIXED LEACHING FRACTION, VARIABLE ET, AND UNIFORM UPTAKE DISTRIBUTION

Figure 11

The large differences in final solute concentration in the variable uptake case are due to a disruption of both water flux and water content. Aside from storage changes, the water flux at any depth is equal to the input flux minus the water extraction rate in the profile above that depth, which varies for different uptake patterns. Extraction thus affects not only the movement of salt and water, but the water content of the layer (which will adjust to the drainage flux) and concentrations may be greatly affected.

Knowledge of the water extraction pattern from the root zone is unfortunately very difficult to obtain experimentally when the divergence of the water flux is large relative to the storage changes (Flühler et al., 1976). Furthermore, the relative uptake is likely to change during the course of an experiment either due to root growth and death, or because the water becomes less available in some regions than in others. In our salinity experiment, the upper portions of the root zone are subjected to increasing amounts of osmotic stress as the concentration of the soil solution rises. Figure 10 is a graph of the matric and osmotic potentials for the eight lysimeters receiving high saline input 109 days after commencement of the wheat experiment. Even though the entire root zone is moist, the extraction **would** tend to move to lower depths as the salinity is increased. In addition, it is highly unlikely that root density or water extraction is uniform across the lysimeter.

The model was also used to make long-term simulations, as shown in Fig. 11, which is a one-year calculation of solute concentrations for leaching fractions of 0.1 and 0.3. Evapotranspiration was represented as a fraction of long term pan evaporation records for Riverside, and uptake was assumed to occur uniformly in the top 100 cm. Significant is the fact that the lower leaching fraction has not reached steady state. Also, the concentrations of the different leaching fraction cases are quite similar during the time of transition even without considering any variability.

CONCLUSIONS

The observed variation in salt concentration found between sensors at comparable depths has been shown to be influenced far more by variability in the water uptake distribution than by changes in the assumed conductivity of the soil or by input variations. This places severe restrictions on simulation of water and salt movement within the root zone.

At the same time, however, it suggests that calculation of material transport below the root zone may not be as severely limited by uncertainty in the soil transport coefficients as had previously been suggested (Nielsen et al., 1973), provided that one can obtain reliable estimates of input water volumes and plant and soil evaporation.

Finally, the period of transition between new and old irrigation management can be quite long, during which time reliance on soil sensors to provide feedback for irrigation levels is likely to cause great errors.

LITERATURE CITED

Flühler, H., M. S. Ardakani, T. E. Szuszkiewicz, and L. H. Stolzy. 1976. Field measured water uptake of Sudan grass roots affected by fertilization. Agron. J. (in press).

Gardner, W. R. 1965. Movement of nitrogen in soil. In W. V. Bartholomew and F. E. Clark (eds.). Soil Nitrogen. Amer. Soc. Agron. Monograph 10.

Jury, W. A., W. R. Gardner, P. G. Saffigna, and C. B. Tanner. 1976. Model for predicting simultaneous movement of nitrate and water through a loamy sand. Soil Science 122:36-43.

Nielsen, D. R., J. W. Biggar, and K. T. Erh. 1973. Spatial variability of field-measured soil-water properties. Hilgardia 42:215-260.

Rose, C. W., W. R. Stern, J. E. Drummond. 1965. Determination of hydraulic conductivity as a function of depth and water content for soil in situ. Aust. J. Soil Res. 3:1-9.

FATE OF SALTS FROM WATER AND MANURE IN A 4-YEAR FIELD EXPERIMENT [1]

P.F. Pratt [2], S. Davis [3], D.C. Adriano [2], S.E. Bishop [2] and A.E. Laag [2]

INTRODUCTION

The effects of the use of animal manures on irrigated lands on the quality of underground waters are increased soluble salts and NO_3 concentrations that result from leaching of these constituents from the root zone of the soil (Adriano et al., 1971). This problem of leaching of soluble salts is of concern in the Chino-Corona Basin located about 40 km east of Los Angeles, California. This basin has about 200,000 dairy cows or cow equivalents concentrated in an area of limited cropland. The underground waters are used extensively for municipal, industrial and agricultural supplies. Also of concern is the fact that groundwaters from the Chino-Corona Basin move laterally into the Santa Ana River where they go downstream and are used for groundwater recharge in Orange County.

The management of irrigated lands to minimize the effects of drainage waters on salt concentrations in receiving waters whether the latter are rivers, lakes, or underground aquifers has received considerable attention in the past few years. The possibility of using high frequency irrigation (Rawlins, 1973; Rawlins and Raats, 1975) for minimizing the leaching volume, maximizing precipitation of salts within the root zone and minimizing mass emissions of salts, as well as minimizing the quantity of water that must be applied to irrigated fields, has been studied. Rhoades et al. (1973, 1974) have shown that reduced drainage volumes effectively increase the precipitation of salts, reduce weathering of soil minerals, and reduce the total salt in the drainage water. Most of this attention to water management for control of leaching of salt has dealt only with the salt in the irrigation water. The general problem of leaching of the salt added in animal manures has received little attention and is a serious problem in many local projects within irrigated areas of the world.

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Because of a potentially serious local problem with leaching of salts in the Chino-Corona Basin from manured lands and because of the general need to know the effects of water management and rates of application of manures on the leaching of NO_3 and soluble salts from manured lands, a field experiment was initiated in 1970. The objectives of this paper are to present data for the leaching from and accumulation of cations in the root zone.

METHODS AND MATERIALS

The soils on which the experimental work was conducted were (1) a Hanford sandy loam (Typic Xerorthent), which has a uniform sandy loam texture to a depth well below the root zone and which has rapid internal drainage, (2) a Ramona sandy loam (Typic Haploxeralf) which has an argillic horizon at about the 0.6 to 1 m depth underlaid by sandy alluvial material, and (3) a Domino silty clay loam (Xerollic Calciorthid) which has a fairly uniform texture to well below the root zone. The experimental area was on the Moreno University Farm located about 16 km south of the Riverside campus of the University of California. All experimental sites were within an area of about 1 km in diameter. On this farm the water that leaves the root zone moves by unsaturated flow through a deep unsaturated zone to a saturated zone at a depth below 30 m.

The experimental plan had two parts. The first was a comparison of six treatments with animal manures, including a check treatment, each at two rates of application of irrigation water on the Hanford soil. The second part was a comparison of one manure treatment, 79 Mt of dairy manure on a dry weight basis per ha per year, on three soils at two irrigation rates. In all cases three replications were used. The plot size was 15 m by 15 m with guard areas of the same size.

The cropping sequence, consisting of barley in the winter and Sudan grass in the summer, went through four complete cycles starting in the fall of 1970. The barley (Hordeum vulgare) cultivar was "Numar", whereas the Sudan grass (Sorghum sudanese) cultivar was "Trudan V". Barley was cut for forage one or two times per year and the Sudan grass was cut two or three times per crop year depending on the season. Forage samples taken at each cutting for each crop were dried at 65°C, ground to pass a 20-mesh screen and were analyzed for mineral elements.

The treatments on the Hanford soil were a check, which received no manure and no fertilizer (irrigation water only), three rates, 40, 79, and 158 Mt per ha per year on a dry weight basis, of solid dairy corral manure and two rates, 21 and 42 Mt per ha per year on a dry weight basis, of liquid manure. The solid manure averaged 69% dry matter, whereas the liquid manure averaged 11% dry matter. The liquid manure came from a feedlot for which the manure was collected under slatted floors and hauled to the field each day. The manures added to experimental plots were disced into the soil within 48 hours after application. Half of the yearly rate of manure was added at the time the land was prepared for barley and the other half at the time the land was prepared for Sudan grass.

The solid manure was air dried in the greenhouse before being analyzed for mineral constituents. The liquid manure was analyzed without drying. Systematic sampling of manures as they were spread on plots provided the samples analyzed in the laboratory. Both types of manures were spread from equipment mounted on hauling trucks. The dry weight of manures added were calculated from total weights of materials delivered by the trucks and laboratory determinations of the dry weight contents of the applied materials. Because water contents were determined after the manures were applied the dry weights added per year varied with water contents and the rates used here are averages for the four years of the experiment.

The two rates of irrigation water used were (1) an arbitrarily selected amount that by experience was judged to be adequate for optimum production, or a level that would meet the evapotranspiration (ET) demand and (2) this selected amount plus 33%. The actual amounts of water added averaged 114 and 142 surface cm per year, respectively, for the low and high rates. Water was added by a sprinkler system on a regular schedule. The higher rate of application was obtained by letting the sprinkler system run 33% longer during each irrigation schedule.

At the end of the 4-year experimental period, soil samples were taken from ten cores per plot to a depth of 4.5 m. Samples were taken at 0.3 m (1 ft) intervals and all samples from each depth interval for each plot were composited to obtain samples for analyses, providing a total of 15 samples per plot. This sampling procedure was estimated to give plot means for NO_3^- and Cl^- concentrations in the 1.5 and 4.5 m depth within 20% of the true means at the 0.95 confidence level as estimated from a statistical analysis of data from 10 cores of one plot for each soil for which each depth interval sample from each core was analyzed individually (Pratt et al., 1976).

Soil samples were weighed at the time they were collected. They were then air dried, weighed again and the weight loss was taken as an estimate of the field water content. The airdried samples were then analyzed for soluble constituents by the saturated paste-saturation extract technique (U.S. Salinity Laboratory Staff, 1954). Concentrations of ions in the saturation extract were multiplied by the ratio of water content in the saturated paste to the field water content to obtain estimated concentrations in the water that had percolated beyond the rooting depth.

The root zone was considered to be limited to the 0 to 1.5 m depth. Thus, the water in the 1.5 to the 4.5 m depth was assumed to be that which had escaped the root zone and was in the process of percolation towards the saturated zone. The average concentration of each individual ion in the water of the below-rooting depth was multiplied by a drainage volume to obtain an estimate of the amount leached during the 4-year experimental period. The volume of percolating water was estimated from a Cl^- balance. The total Cl^- added in irrigation water and in manures minus the Cl^- removed in harvested crops was expressed as an effective Cl^- concentration in the irrigation water and was divided by the Cl^- concentration in the percolating water (1.5 to 4.5 m depth) to obtain a leaching fraction

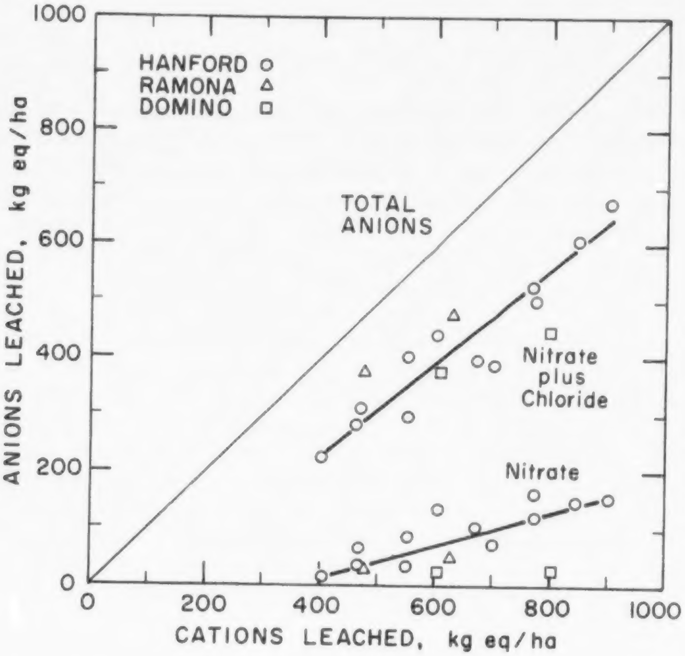

Figure 1. Relationships between anions leached and cations leached. The line for total anions assumes that the anions equaled the cations when expressed on an equivalent basis.

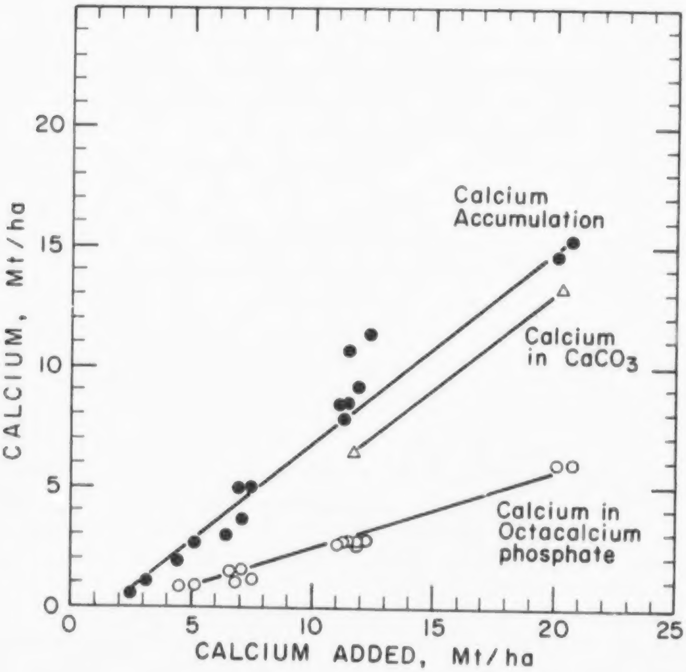

Figure 2. Relationships among Ca accumulation in the root zone, Ca accumulation as $CaCO_3$ in the Hanford soil, calculated Ca accumulation as $Ca_4H(PO_4)_3$ assuming all P fixed was in this form, and total Ca added.

(L.F.). The L.F. times the irrigation water added gave an estimate of the volume of water leached from the root zone. Because of increased dissolution of carbonates and gypsum in saturation extracts as compared to water contents in the field the amounts of cations leached are considered to be overestimated and to represent possible upper limits. Also, the amounts of cations accumulated in the root zone are underestimated and are considered to be lower limits.

The irrigation water, used on the Hanford and Domino soils, came from one source and had the following average concentrations of ions, expressed in meq per l: Ca^{+2}, 2.60; Mg^{+2}, 0.89; Na^{+}, 5.20; K^{+}, 0.15; NO_3^{-}, 0.53; $SO_4^{=}$, 0.72; Cl^{-}, 4.97; and HCO_3^{-}, 2.62. This water had an EC of 0.918 mmhos. The water used on the Ramona soil came from a different source and had the following concentrations of ions expressed in meq per l: Ca^{+2}, 2.50; Mg^{+2}, 0.76; Na^{+}, 5.13; K^{+}, 0.17; NO_3^{-}, 0.26; $SO_4^{=}$, 0.60; Cl^{-}, 5.38; and HCO_3^{-}, 2.32. This water had an EC of 0.898 mmhos. Both waters have Na^{+} and Cl^{-} as the dominant ions and both have nearly the same total salts. From a practical point of view, they are essentially the same water.

RESULTS

Data for the amount of irrigation water applied, the L.F., the volume of leachate, and the Cl^{-} concentration in the leachate are presented in Table 1. The volume of leachate was consistently lower for the Ramona and Domino soils than for the Hanford except for the high irrigation treatments in combination with the highest rate of solid manure on the Hanford. For this rate of manure on the Hanford the L.F. was the same for both irrigation treatments. Also, the volume of leachate at the high irrigation treatment was lower than for the same irrigation treatment at all other rates of manure on the Hanford soil. No explanation is offered for these anomolous results. The concentration of Cl in the leachate increased linearly with increase in the rate of manure application for each irrigation treatment for the Hanford soil, but, the Cl concentrations in the leachate from the Ramona and Domino soils were higher than in the leachate from the same treatments on the Hanford soil.

Data for Ca added, removed in forage, leached from the root zone, and accumulated in the root zone are presented in Table 2 and similar data for Mg, Na, and K are presented in Tables 3, 4, and 5, respectively. In each case the amount accumulated was calculated as that added minus the sum of that removed in forage plus leached from the root zone. Except for K in the check treatment and the lowest rates of manure, removal of cations in forage was a small fraction of the totals applied. With each cation the amount removed in forage increased very little with increase in rates of manures. Sodium was the dominant cation in the drainage water and as expected very little K leached from the root zone.

The relationship between anions leached and cations leached is presented graphically in Fig. 1. The line for total anions assumed that total anions equaled total cations on an equivalent basis. Bicarbonate and

Table 1. Data for amount of irrigation water applied during the 4-year experimental period, the leaching fraction, the volume of leachate and the Cl^- concentration in the leachate

Soil	Manure	Annual rate, dry weight basis	Irrigation water applied	Leaching fraction	Volume of leachate	Chloride concentration in leachate
		Mt/ha	cm		cm	meq/l
Hanford	none	-	456	0.28	128	16.3
		-	568	0.37	210	12.6
	liquid	21	456	0.24	109	22.5
		21	568	0.36	204	14.6
		42	456	0.25	114	26.7
		42	568	0.35	199	18.2
	solid	40	456	0.23	105	23.6
		40	568	0.35	199	15.8
		79	456	0.21	96	32.6
		79	568	0.36	204	18.4
Ramona		79	464	0.15	70	48.9
		79	613	0.23	141	30.3
Domino		79	502	0.12	60	58.4
		79	655	0.24	157	26.7
Hanford		158	456	0.24	109	42.3
		158	568	0.24	136	38.0

Table 2. Data for Ca added, removed in forage, leached from the root zone and accumulated in the root zone.

Soil	Manure type	Annual rate, dry weight basis	Irrigation	Calcium			
				Added	Removed in forage	Leached from root zone	Accumulated in root zone
		Mt/ha		--------------------Mt/ha--------------------			
Hanford	none	0	1	2.43	0.24	1.72	0.47
		0	2	3.04	0.22	1.89	0.93
	liquid	21	1	4.53	0.36	2.36	1.81
		21	2	5.14	0.37	2.13	2.64
		42	1	6.63	0.33	3.38	2.92
		42	2	7.24	0.34	3.31	3.59
	solid	40	1	6.85	0.39	1.77	4.69
		40	2	7.46	0.37	2.19	4.90
		79	1	11.27	0.34	3.19	7.74
		79	2	11.88	0.35	3.11	8.42
Ramona		79	1	11.16	0.33	2.41	8.42
		79	2	11.92	0.38	2.32	9.22
Domino		79	1	11.51	0.38	0.46	10.67
		79	2	12.34	0.37	0.66	11.31
Hanford		158	1	20.10	0.26	5.26	14.58
		158	2	20.71	0.26	5.21	15.24

Table 3. Data for Mg added, removed in forage, leached from the root zone and accumulated in the root zone.

Soil	Manure type	Annual rate, dry weight basis	Irrigation	Magnesium Added	Magnesium Removed in forage	Magnesium Leached from root zone	Magnesium Accumulated in root zone
		Mt/ha		-----------------	Mt/ha	-----------------	
Hanford	none	0	1	0.49	0.12	0.40	-0.03
		0	2	0.62	0.11	0.36	0.15
	liquid	21	1	1.59	0.24	0.52	0.83
		21	2	1.71	0.23	0.60	0.88
		42	1	2.69	0.24	0.68	1.77
		42	2	2.81	0.22	0.76	1.83
	solid	40	1	1.70	0.23	0.54	0.93
		40	2	1.82	0.19	0.67	0.96
		79	1	2.91	0.21	0.64	2.06
		79	2	3.03	0.21	0.60	2.22
Ramona		79	1	2.85	0.18	0.65	2.02
		79	2	2.99	0.19	0.58	2.22
Domino		79	1	2.96	0.22	0.32	2.42
		79	2	3.12	0.19	0.44	2.49
Hanford		158	1	5.33	0.16	1.07	4.10
		158	2	5.45	0.15	1.14	4.16

Table 4. Data for Na added, removed in forage, leached from the root zone and accumulated in the root zone.

				Sodium			
Soil	Manure type	Annual rate, dry weight basis	Irrigation	Added	Removed in forage	Leached from root zone	Accumulated in root zone
		Mt/ha		---------	--------Mt/ha	---------	---------
Hanford	none	0	1	5.43	0.15	6.51	-1.23
		0	2	6.76	0.13	9.61	-2.98
	liquid	21	1	6.76	0.26	6.94	-0.44
		21	2	8.09	0.25	11.59	-3.75
		42	1	8.08	0.28	8.50	-0.70
		42	2	9.41	0.26	12.22	-3.07
	solid	40	1	6.63	0.25	7.41	-1.03
		40	2	7.97	0.24	12.18	-4.45
		79	1	7.84	0.24	7.77	-0.17
		79	2	9.17	0.22	12.81	-3.86
Ramona		79	1	7.82	0.28	6.92	+0.62
		79	2	9.65	0.29	10.51	-1.15
Domino		79	1	8.36	0.31	12.81	-4.76
		79	2	10.19	0.25	16.76	-6.82
Hanford		158	1	10.25	0.22	11.18	-1.15
		158	2	11.58	0.21	12.32	-0.95

Table 5. Data for K added, removed in forage, leached from the root zone and accumulated in the root zone.

Soil	Manure type	Annual rate, dry weight basis	Irrigation	Potassium			
				Added	Removed in forage	Leached from root zone	Accumulated in root zone
		Mt/ha		Mt/ha			
Hanford	none	0	1	0.26	1.30	0.22	-1.26
		0	2	0.33	1.10	0.35	-1.12
	liquid	21	1	2.96	2.62	0.25	0.09
		21	2	3.03	2.44	0.33	0.26
		42	1	5.66	2.67	0.26	2.73
		42	2	5.72	2.40	0.32	3.00
	solid	40	1	5.22	2.45	0.19	2.58
		40	2	5.28	2.35	0.35	2.58
		79	1	10.18	2.82	0.23	7.13
		79	2	10.24	2.63	0.43	7.18
Ramona		79	1	10.22	2.37	0.18	7.67
		79	2	10.32	2.38	0.26	7.68
Domino		79	1	10.20	2.61	0.11	7.48
		79	2	10.29	2.46	0.12	7.71
Hanford		158	1	20.09	2.30	0.37	17.42
		158	2	20.16	2.05	0.56	17.55

$SO_4^=$ were not determined and thus a summation of determined anions could not be plotted. On an average, about 60% of the total anions that must have leached consisted of Cl^- plus NO_3^-, leaving about 40% for the sum of HCO_3^- and $SO_4^=$.

The relationships between Ca accumulation in the root zone and Ca added and between a measured Ca increase as $CaCO_3$ in the soil and a calculated Ca increase in the form of $Ca_4H(PO_4)_3$ in the soil and Ca added are presented graphically in Fig. 2. The Ca increase as $CaCO_3$ was determined from the $CaCO_3$ determined in the manured plots minus that determined in check plots for two manure treatments on the Hanford soil. The amount of Ca in $Ca_4H(PO_4)_3$ was calculated from the total P fixed in the soil assuming that P was fixed in this form.

DISCUSSION

The accumulation of cations within the root zone is probably a result of a number of factors including (1) an increase in soluble salts, (2) an increase in the cation exchange capacity (CEC), (3) fixation of K in micaceous layer-lattice silicates, and (4) the precipitation of Ca and/or Mg as carbonates, phosphates and silicates. The precipitation of K as taranakite, a complex K-Al phosphate, is also possible. The volume of water that percolated beyond the root zone during the 4-year period of treatment was sufficient that accumulation of salinity in the root zone was small relative to the cations accumulated. The difference in soluble salts in the root zone of the highest manure treatment and the check treatment was only 6% of the total cations accumulated in the root zone of the highest treatment. Also, comparison of cation-exchange capacities (CEC) showed no increase with increase in rate of manure. Evidently any increases in CEC from increase in organic matter was balanced by a decrease in CEC as a result of K entrapment in micaceous clays. Thus, cation fixation and precipitation into insoluble forms must be the mechanisms of accumulation of cations in the root zone.

During the preparation of this manuscript, two methods of calculating amounts of each cation leached were used. The first was to multiply the concentration of the cation in the saturation extract times the volume of percolating water. This method was considered to give values that are too low and to give lower limits to the amounts of cations leached. The second method, which was the one used in this report, was to convert concentrations to a soil solution or field water content basis and then to multiply this concentration by the volume of percolating water. This second method is considered to give values that are too high and to give upper limits for cations leached. Because of dissolution of sulfates and carbonates, and perhaps other salts, the total amount of soluble salt in a saturation extract is expected to be larger than in the water in the unsaturated state found in the field. The difference between the amounts of total cations leached as calculated by these two methods was a relatively small fraction of the total cations added. Data by Eaton et al. (1960) for comparisons of concentrations of Ca^{2+}, Mg^{2+} and Na^+ in solution at 0.1 bar suction and in saturation extracts suggest that the second method would be much more reliable, and data by Reitemeier (1945)

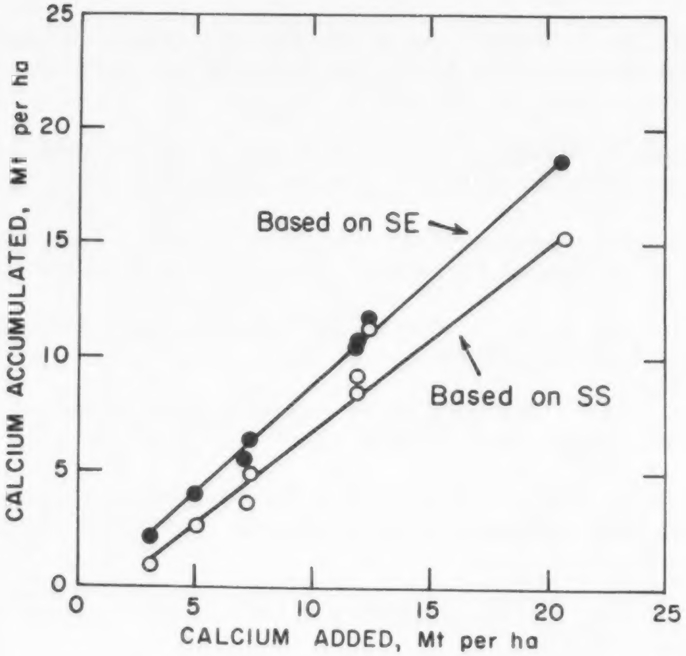

Figure 3. Relationships between Ca accumulation in the root zone and Ca added for calculated Ca leached based on soil solution (SS) and saturation extract (SE) concentrations.

on the effect of water contents on the dissolved and exchangeable ions in arid regions soils also suggests that conversion to concentrations in the unsaturated field situation would be the more accurate of the two methods. In any event, leaching of cations as reported here is slightly overestimated and the accumulation of cations in the root zone is slightly underestimated. However, the relative amounts leached and accumulated relative to additions are probably valid. Figure 3 presents the relationship between Ca accumulation and Ca added for both methods of calculating Ca leached. The data based on the soil solution (SS) concentration are about 20% higher than those based on saturation extract (SE) concentrations for higher amounts of Ca accumulation. The real value for Ca accumulation is probably somewhere between the two sets of data in Fig. 3 and perhaps closer to the SS than the SE set. However, the regression of the real values against Ca added must be nearly the same as that for each set of data. The suggestion from Fig. 3 is that the data in this paper give an accurate presentation of the relative amounts of cations leached from and accumulated in the root zone.

LITERATURE CITED

Adriano, D. C., P. F. Pratt, and S. E. Bishop. 1971. Nitrate and salt in soils and groundwaters from land disposal of dairy manures. Soil Sci. Soc. Amer. Proc. 35:759-762.

Eaton, F. M., R. B. Harding, and T. J. Ganje. 1959. Soil Solution extractions at tenth-bar moisture percentages. Soil Sci. 90:253-258.

Pratt, P. F., J. E. Warneke, and P. A. Nash. 1976. Sampling the unsaturated zone in irrigated field plots. Soil Sci. Soc. Amer. J. 40:277-279.

Rawlins, S. L., and P. A. C. Raats. 1975. Prospects for high-frequency irrigation. Science 188:604-610.

Rawlins, S. L. 1973. Principles of managing high frequency irrigation. Soil Sci. Soc. Amer. Proc. 37:626-629.

Reiteimeir , R. F. 1945. Effect of moisture content on the dissolved and exchangeable ions of soils of arid regions. Soil Sci. 61:195-214.

Rhoades, J. D., J. D. Oster, R. D. Ingvalson, J. M. Tucker, and M. Clark. 1974. Minimizing the salt burdens of irrigation drainage waters. J. Environ. Qual. 3:311-316.

Rhoades, J. D., R. D. Ingvalson, J. M. Tucker, and M. Clark. 1973. Salts in irrigation drainage waters: I. Effects of irrigation water composition, leaching fraction, and time of year on the salt compositions of irrigation drainage waters. Soil Sci. Soc. Amer. Proc. 37:770-774.

U. S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U. S. Department of Agriculture Agricultural Handbook No. 60. U.S. Government Printing Office, Washington, D.C.

CALCULATION AND PREDICTION OF THE SALT REGIME OF LOWLAND SOILS UNDER INFLUENCE OF GROUNDWATER SALINIZATION

N. Plamenac, M. Viković, and M. Matić 1/

INTRODUCTION

Salt regime calculations and predictions have been made and applied for the purpose of solving the problems of protecting and reclaiming the low-lying alluvial flat land along the Danube, in the area influenced by a backwater created after the erection of the Djerdap Dam.

The area of alluvial flat studied is protected from high waters by dikes. The background of this flat is formed by loessial terraces of the Panonian Plain.

By the end of the last and at the beginning of this century, dikes were constructed along the Danube. Under such circumstances the soil water and salt regime in the protected areas were changed, which consequently led to pronounced salinization of soil in some places. With further deterioration of the ground-water regime in these areas, conditions were created for even more intensive salinization. In order to understand the consequences the changes of the ground-water regime had on the salt regime of soil, a methodology was worked out and employed for calculating and predicting these consequences.

The results of calculation and prediction of the soil salt regime, under natural and backwater conditions, and in combination with a different drainage regime, served as a basis for evaluating the economic effects of drainage and for selecting its most favorable forms.

NATURAL CONDITIONS

The area of the low-lying alluvial flat land, for which salt regime calculations and predictions have been made using the methodology worked out, is characterized by approximately identical conditions throughout. Therefore, the character of salinization is essentially the same over the whole area studied.

The mean annual rainfall in the area is 638 mm, of which about 450 mm occurs during the period of vegetation (April-October), and the mean annual temperature is 11.3°C.

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The soils are mostly hydromorphous, clayey and in some places slightly saline, depending on the topography. The salts in the soil mostly originate from the ground waters. The solute over the entire soil profile is saturated with Mg and Ca salts, mostly of HCO_3 and SO_4 composition. The concentration of the soluble salts in the ground waters of the water-bearing strata in the Danube zone ranges from 200 to 300 mg/l, and in the zone of the loessial terrace from 500 to 1300 mg/l.

The lower part of the surface layer consists mainly of redeposited loess and fine sand. Strata of coarse sand or gravel lie under this layer, and these form the main water-bearing horizons. The horizons have very pronounced filtration characteristics, against the more or less impermeable top layer. The depth of the topsoil layer ranges from 2 to 6 m, and of the water-bearing layer from 10 to 20 m. The river bed cuts into the lower water-bearing horizon, hence the water regime in the Danube propagates rapidly over a relatively wide zone of the alluvial lowland (1-3 km).

The backwater, because of the influence of Djerdap Dam, changes the water level regime on the Danube within the area studied, rising during periods of medium and low water discharge from the dam. As a consequence of these changes in the water regime, there are also changes in the groundwater regime and the water and salt regime of the soil.

METHODOLOGY

The methodology of the salt regime calculation and prediction has been worked out and applied to a hydrogeological medium which may be described as a two-layer porous medium 2/. This methodology is based on a numerical solution of partial differential equations describing the flow of water in a two-layer medium and of equations describing the salt movements.

For solving the differential equations the method of finite increments has been employed. According to this, non-steady state flow of water and salts is viewed as a series of successive steady states, occurring in the time interval ΔT. In this, the elements of water balance, computed for the appropriate time intervals ΔT, have been used as the input data for calculating the salt balance for the same interval.

The problem is analyzed in two dimensions, within the profiles along the area of flow. For the case studied, the computational profiles are perpendicular to the direction of the Danube.

2/ Here a two-layer porous medium is understood as a porous medium, consisting of two separate layers, of which the lower is much more permeable than the upper one. Under such conditions, the flow in the lower, water-bearing layer may be considered to take place in the horizontal, and in the top one in the vertical direction (see Fig. 1).

This methodology has been adapted for computer processing [3]. This enabled a large number of parameters to be introduced and a more reliable analysis and interpretation of the real conditions.

For a more clear comprehension of the methodology employed in calculating the salt regime, the basic elements of the methodology for calculating the ground-water regime are considered first.

The methodology of calculation of the water regime under the flow conditions in a two-layer porous medium

The flow of ground water in a two-layer porous medium, in the case of a two dimensional (horizontal) flow (Fig. 1), may be described by the following set of partial differential equations:

$$\frac{\partial^2 H}{\partial x^2} = \frac{K_m}{M \cdot K_M} \left(\frac{H - h}{h}\right) \qquad (1)$$

$$\frac{\partial h}{\partial t} = \frac{K_m}{\mu} \left(\frac{H - h}{h}\right) + \frac{W}{\mu} \qquad (2)$$

where:

W - is the infiltrated volume of water. A positive sign indicates that at a given moment water is infiltrated from the surface of the terrain into the subsoil; a negative sign that evapotranspiration is greater than the infiltration.

μ - is the effective porosity of the upper, low-permeability layer.

H - is the thickness of wetted zone above aquifer layer.

h - is the thickness of free water zone above aquifer layer.

M - is the thickness of aquifer layer.

K_m- is water flux in upper layer.

K_M- is water flux in aquifer layer.

x - horizontal distance from water source.

For solving the above set of differential equations, a numerical method has been worked out, based on the method of finite increments, allowing a simple use of computers in calculating the ground-water regime and water-balance elements.

The computational profile is divided into a number of sections (Δx) with constant geometrical, hydrogeological, and hydrodynamic characteristics.

From equation (2) it may be seen that the method makes use also of the elements of the "vertical balance" (infiltration from precipitation and evapotranspiration). In this connection, for the climatic and soil conditions in the area studied, relationships between precipitation and infiltration, and between evaporation from the open and ground waters, have been used. These relationships are shown in graphical form in Figs. 2 and 3.

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[3] A CDC-3600 computer has been used for this purpose.

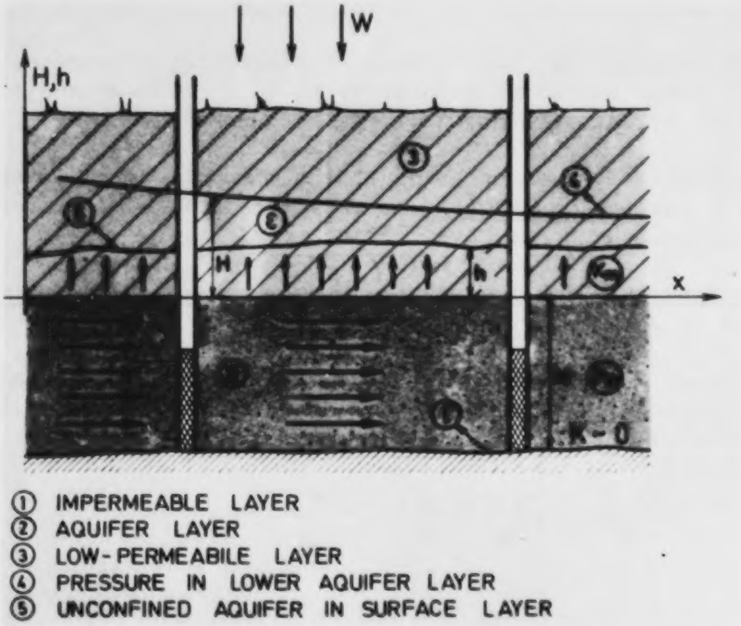

W
H,h
H
h
x
K=0
③
④
①
⑤
②
① IMPERMEABLE LAYER
② AQUIFER LAYER
③ LOW-PERMEABILE LAYER
④ PRESSURE IN LOWER AQUIFER LAYER
⑤ UNCONFINED AQUIFER IN SURFACE LAYER

Fig. 1. Schematization of a two-layer porous medium

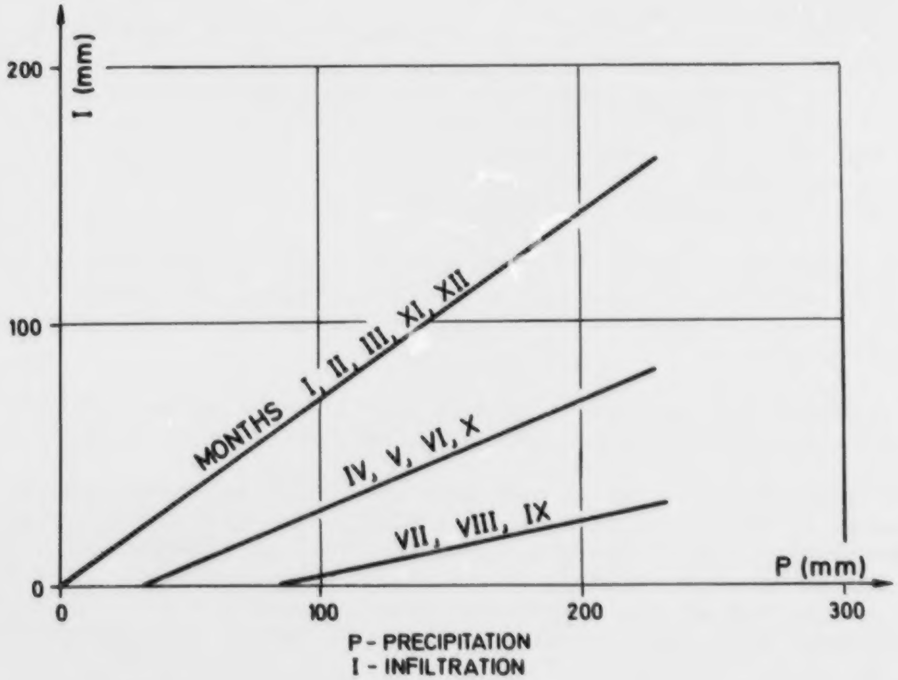


Fig. 2. Relationship between precipitation and infiltration used for hydraulic calculations

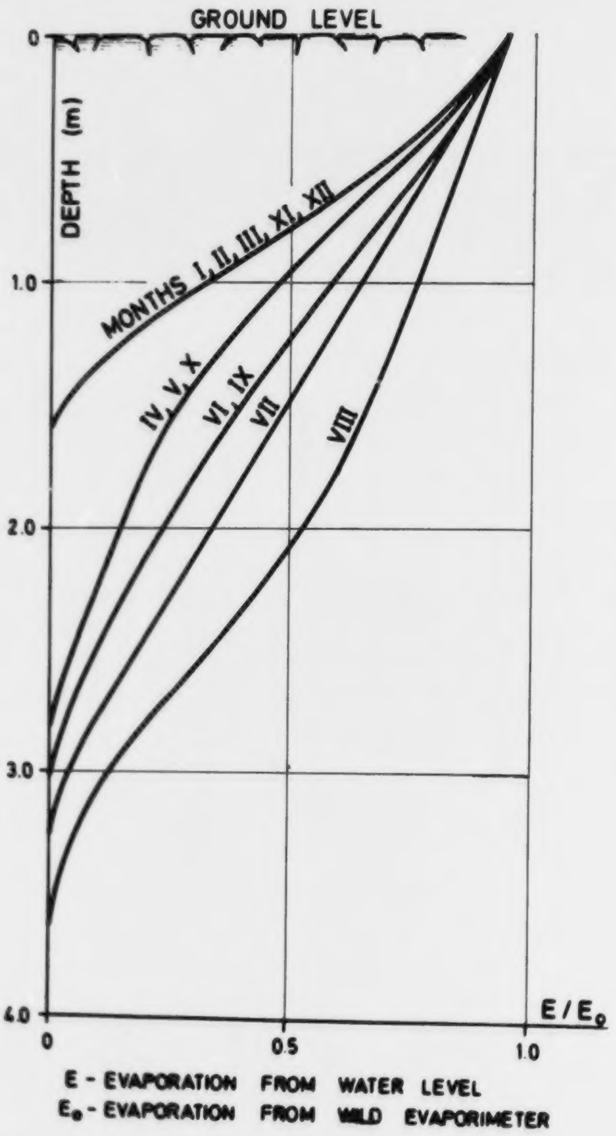


Fig. 3. Relationship between E/E_0 and groundwater depth used for hydraulic calculations

As a result of the above described methodology, for the given geometrical and hydrodynamic characteristics of a porous medium, quantitative values are obtained for all elements of the water balance along the computational profile, for every separate section.

For determining the representative hydrodynamic and geometrical characteristics along the computational profiles, the method of adjustment is employed, aiming at correlating the computational results with those obtained in the field. Figure 4 shows an example of adjustment of a computational profile on the mathematical model constructed by the described methodology.

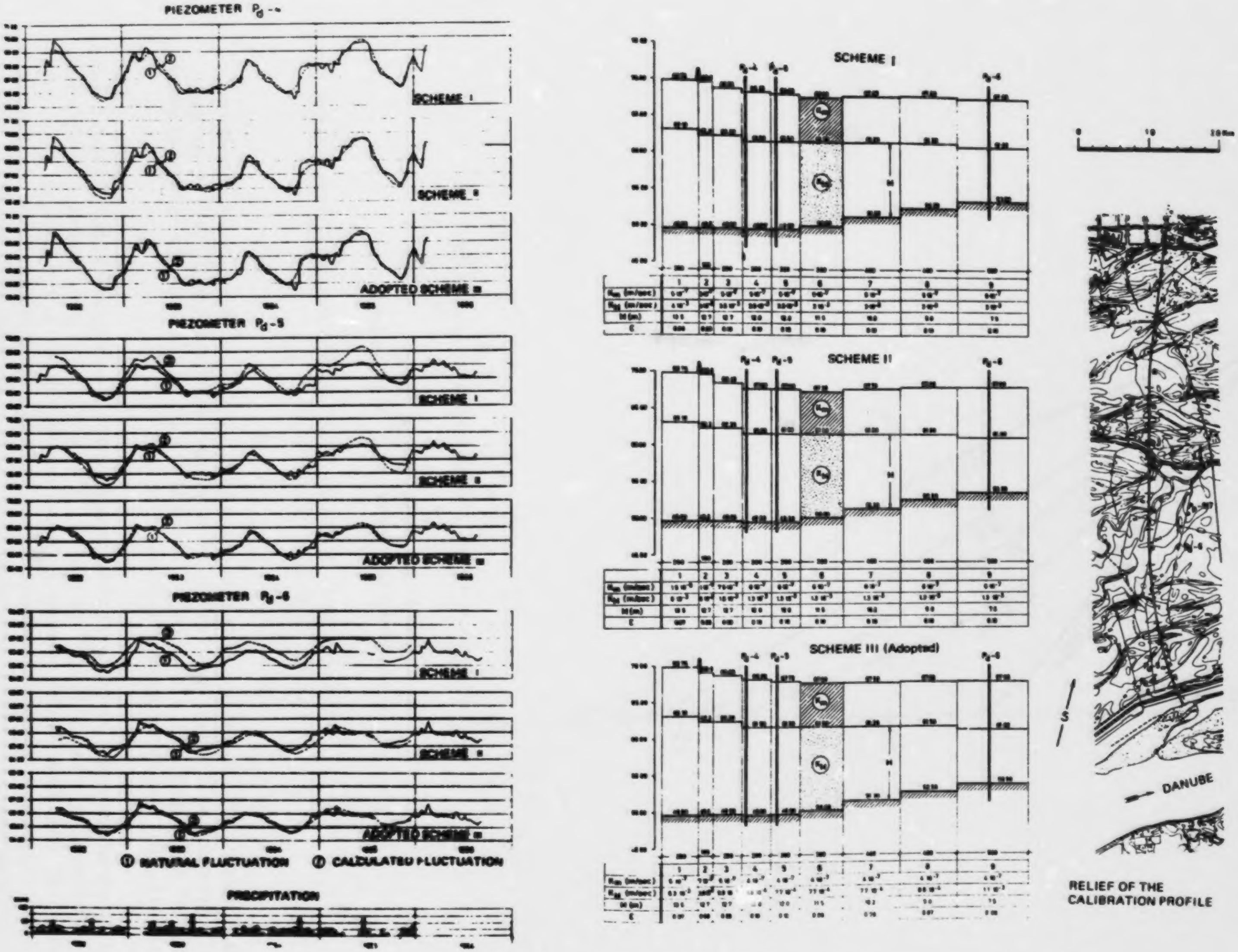


Figure 4. Process of calibrating the mathematical model for three schematizations of hydrological conditions.

The methodology of calculating and predicting the soil salt regime

The methodology of calculating and predicting the salt regime in soil is based on a numerical solution of the partial differential equation describing the mass transfer in a porous medium

$$\mu\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial t^2}\right) - \left[\frac{\partial (VC)}{\partial x} + \frac{\partial (VC)}{\partial z}\right] + \beta(C_n - C) \qquad (3)$$

where:
C - concentration of salt in water
D - diffusion coefficient
β - solubility of salt in water
V - flow rate of water in a porous medium
(filtration-Darcy's rate)
C_n- boundary saturation
x - horizontal thickness
z - vertical thickness
μ - as before
t - time

In working out this methodology, the following assumptions have been made:

- The role of diffusion in salt transfer may be neglected as regards the transfer of salt due to water flow ($D = 0$).
- The problem of transfer of readily soluble salts is considered such that the term

  $$\beta\ (C_n - C)$$

  may be neglected.

In this way, equation (3) becomes

$$\mu\frac{\partial C}{\partial t} = -\frac{\partial (VC)}{\partial x} - \frac{\partial (VC)}{\partial z} \qquad (4)$$

The differential equation (4) is solved by the method of finite increments. In this, velocities V are given the values calculated via the flows obtained from the calculation of the water regime. Mutual relationships of these calculations determine that the time and geometrical elements of division should be the same in both cases.

In practical application of this method, calculations of the salt transfer by sections (Fig. 5) are made simultaneously for the lower, water-bearing and the upper layers:

The lower, water-bearing layer (zone 1)

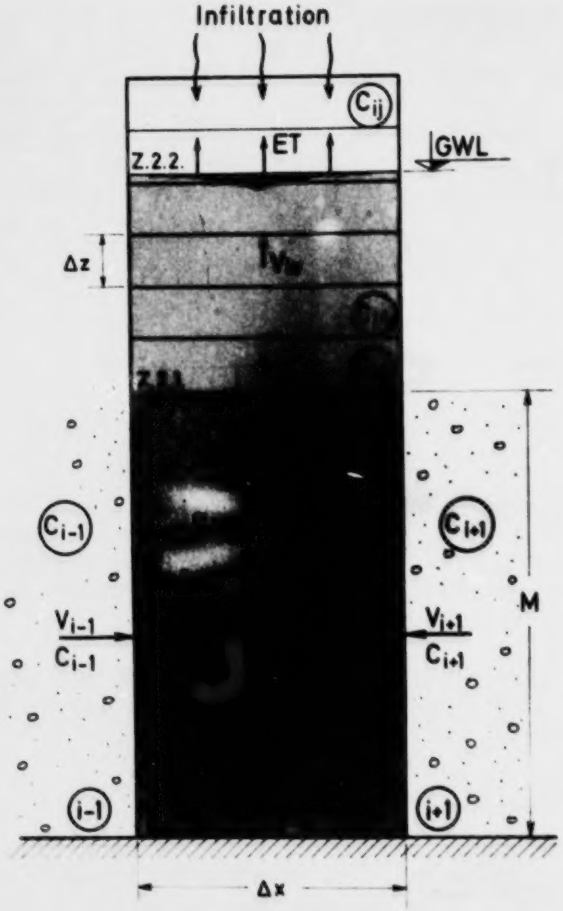
Concentrational changes in the lower, water-bearing layer for every computational section separately, are obtained as a result of the horizontal flow (inflow or outflow from the adjacent sections) and outflow of water from the upper layer (vertical flow).

The upper, low-permeable layer (zone 2)

This zone, in which vertical flow takes place, is divided into several layers (increment Δz). Every elementary layer is ascribed homogeneous hydrochemical characteristics.

From the point of water balance elements, this zone may be divided into two sub-zones:

> A belt from the ground water table to the line of contact with the water-bearing layer (subzone 2.1)
>
> In calculating the salt balance in this subzone, it has been assumed that in every computational section in a time interval Δt the vertical (filtration - Darcy's) rate is constant over the whole depth of this belt.


Infiltration
C_{ij}
ET
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GWL
Δz
V_{iz}
Z.2.1
C_{i-1}
C_{i+1}
V_{i-1}
C_{i-1}
V_{i+1}
C_{i+1}
M
i-1
i+1
Δx

Fig. 5. The computational scheme of salt transport

A belt above the ground water table-capillary fringe (subzone 2.2)

The flow of water in this belt is directly affected by the rates of infiltration and evapotranspiration. Here, too, it has been assumed that in every section in a time interval Δt the water flow rate is constant over the whole depth of the capillary fringe.

The above shown methodology of calculating the salt and water regime has been programmed for processing on a computer. As a result of calculating the salt regime of soil, data on the changes in the salt content along the computational profile are obtained as a function of time for a chosen number of sections.

APPLICATION OF METHODOLOGY AND RESULTS

Calculations and prediction of the salt regime of soil have been performed for the area of low-lying alluvial land along the computational profiles defined by the Danube and the background loessial terrace. Computational profiles have been chosen so that they can be considered representative from the point of hydrodynamic characteristics and soil salinization phenomena.

From the preceding extensive research and field work, basic elements have been obtained for working out the mathematical models and precise definition of the initial and boundary conditions required in carrying out the hydrodynamic and salinization regime calculations.

As a result of these calculations, a clear picture has been obtained about the character of the salinization process and of the mechanism of salt movement in soil under different hydrological and hydrodynamic conditions that are predictable in this area.

Figure 6 shows a section of a computational profile (shown in Fig. 4), with the division of the upper layer of soil into 0.5 m elementary horizontal strata (lamellae).

The results of calculating the changes of salt concentration in soil by depth, for two typical points (computational sections), are shown in Figs. 7 and 8. Salt distribution in soil by depth is shown for the four time periods, representing the typical seasonal dynamics.

In this work, calculations of the salt regime have been carried out simultaneously for the natural, undrained and drained backwater conditions.

The increase of salt concentration in soil for these three states of the water regime are shown in Fig. 9. From the results shown, it is clear that on the microlocation, for which the increase of salt concentration is illustrated in Fig. 9, there is a tendency of a moderate increase of soil salinity, even with the natural water regime in the Danube. Under backwater conditions, salinization would be intensified, should drainage, as a measure of controlling the water regime of soil, not be provided. It is clear that the effect of the drainage employed is favorable for the salt regime of soil, because such a drainage practically eliminates any tendency of further salinization.

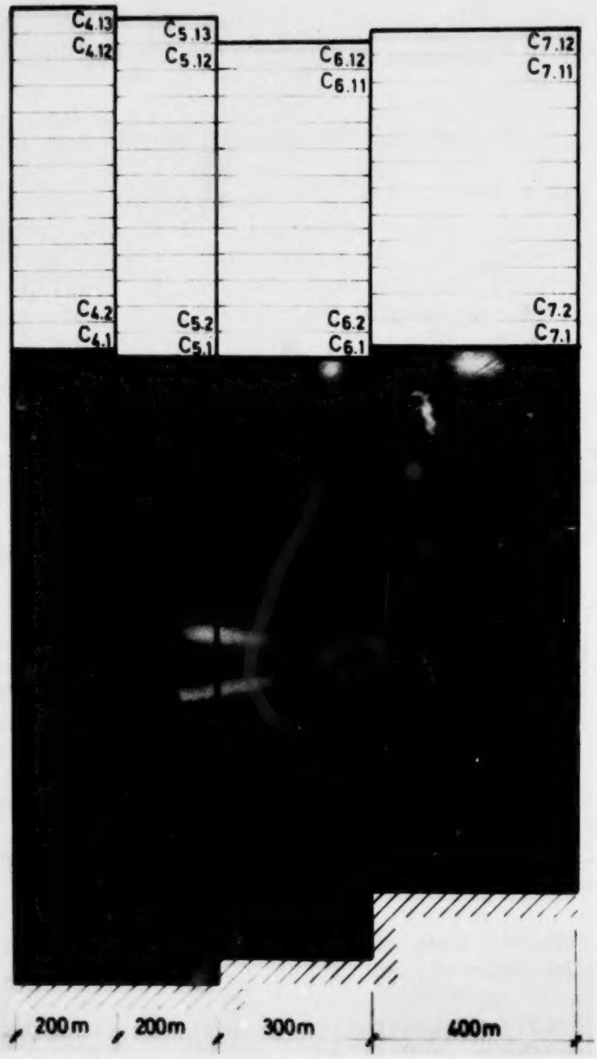
$C_{4.13}$
$C_{4.12}$
$C_{5.13}$
$C_{5.12}$
$C_{6.12}$
$C_{6.11}$
$C_{7.12}$
$C_{7.11}$
$C_{4.2}$
$C_{4.1}$
$C_{5.2}$
$C_{5.1}$
$C_{6.2}$
$C_{6.1}$
$C_{7.2}$
$C_{7.1}$
200m
200m
300m
400m

Fig. 6. The computational scheme for salt balance calculation (connection with scheme 1 - Fig. 4)

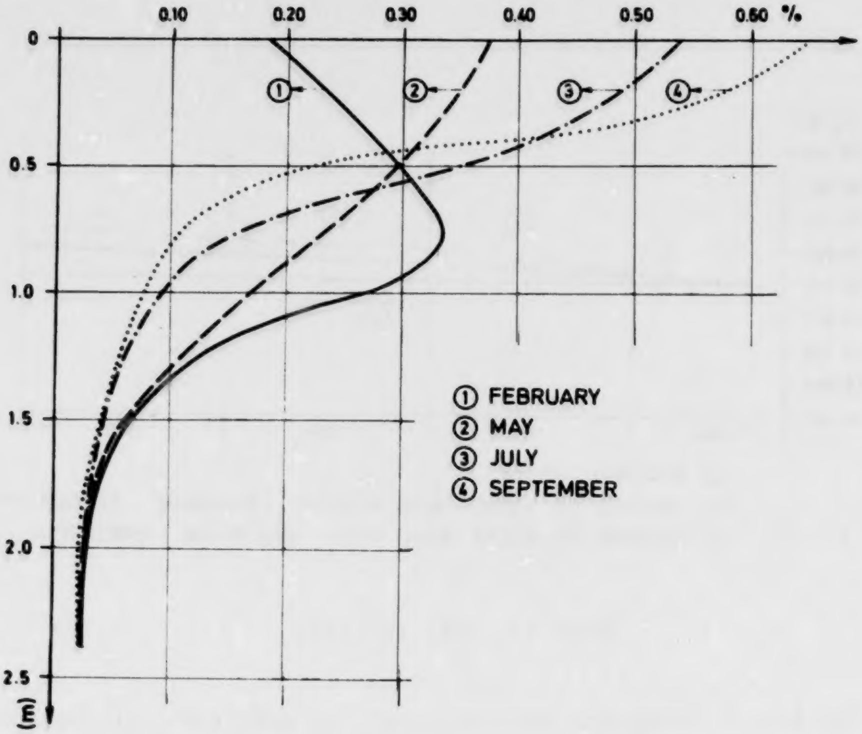

Fig. 7. Soil salt distribution by depth

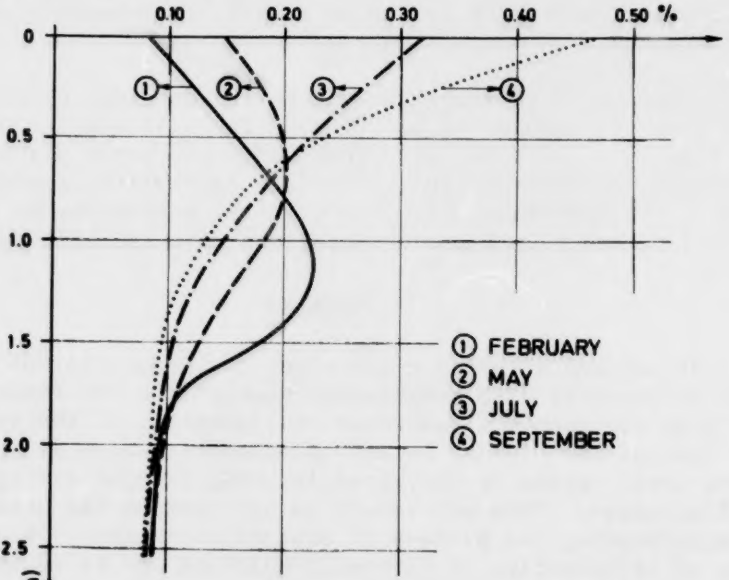

Fig. 8. Soil salt distribution by depth

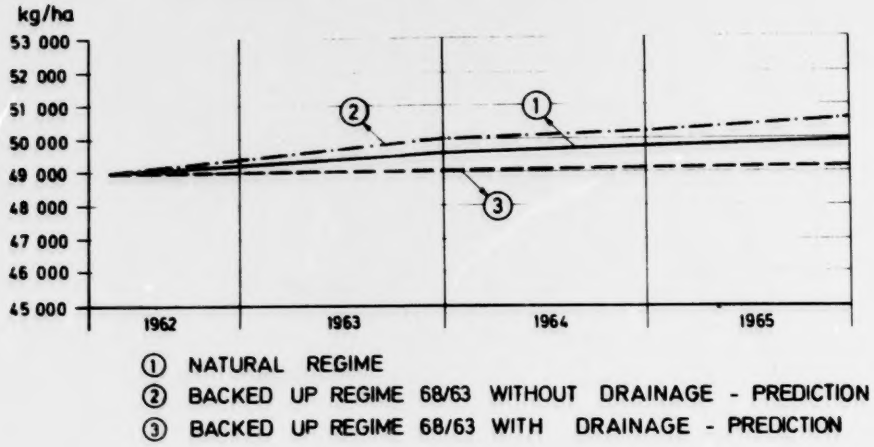

Fig. 9. Soil salinity

The results of these calculations have been used also for mapping the present and future (predicted) salinization regimes at various depths of soil. For the whole area, maps of the predicted regimes of salt concentration in soil have been drawn, with sections for several typical time periods (5, 10, and 20 years). Separate maps have been drawn for three soil layers: 0.0 - 0.5, 0.5 - 1.0 and 0.1 - 2.5 m. Together with other elements, these maps served as a basis for choosing optimum solutions of drainage.

Experience gained in this work points to an advantage of the method employed over the methods of calculating the salt balance on a regional scale. This is so because the method employed, which allows a choice of computational sections of arbitrary size, takes into consideration also the local characteristics. In this way, the method may be employed for smaller areas, and even for microlocations with specific conditions.

SUMMARY

The area of lowland alluvial plain along the Danube in the zone of Belgrade is provided with embankments controlling the river floods, which results in an occurrence of secondary salinization of the soil. Due to the construction of the Djerdap large hydroelectric power plant (1965-1972), the water level regime in the river is being changed during minimum and medium discharges. This may result in aggravating the groundwater regime and in accelerating the process of soil salinization. In order to realize the rate of salinization in altered conditions and to estimate the influence

of various measures, calculation and prediction of the salt regime of lowland soils has been made. The area considered is, in hydraulic view, a two-layer porous medium with clay prevailing in the surface layer. The lower, waterbearing layer, being hydraulically linked with the Danube, consists of sand and gravel. For such hydrogeological conditions a methodology is elaborated for calculation of the groundwater regime, presenting the basis for calculation and prediction of the salt regime of lowland soils in given conditions. The methodology for prediction of salt regime of the soil is founded on the water and salt balance being the consequence of water percolation through the soil. Calculation of the salt regime of the soil resulted in realizing the process of salinization for the existing conditions as well as for a situation when appropriate reclamation works are applied. The practical aspect of this methodology is the possibility of its application to large areas of alluvial plains which could be schematized by a two-layer porous medium. In this case, the calculation and prediction involved an area of 80,000 ha.

LITERATURE CITED

Averjanov, S.F. 1966. Nekotorie voprosi predupreždenia zasolenia orošaemih časti SSSR. Moskovski institut hidromelioracije, Ministrastvo poljoprivrede SSSR. Moskva.

Boreli, M., M. Viković, D. Babac, B. Matić, and N. Plamenac. 1972. The problem of seepage. In Transaction of the "Jaroslav Černi" Institute for Development of Water Resources, vol. XVII, No. 50-53: 191-261.

Plamenac, N. and M. Vuković. 1969. Značaj izučavanja i izrade prognoze vodnog i sonog režima zemljišta za potrebe melioracija. In Prvi kongres o vodama Jugoslavije, Knjiga I, Pa: 108-112.

Plamenac, N. 1976. Water - Salt relationship in the alkali soil of Ulcinj field. In Soil and plant, Acta Biologica Iugoslavica, vol. 20, No. 1-3, 47-62.

Vuković, M. 1967. Groundwater in a two-layer porous media. In Transaction of the "Jaroslav Černi" Institute for Development of Water Resources, vol. XIII. No. 39.

CONVECTIVE TRANSPORT OF SOLUTES IN AND BELOW THE ROOT ZONE

P. A. C. Raats [1]

INTRODUCTION

Two major objectives of research related to the management of saline water for irrigation are

- -- to find the space-time trajectories of parcels of water;
- -- to determine the changes in quality of these parcels.

To meet the first objective, one can turn to a large body of experience with movement of water in saturated and in unsaturated soils. In the past, most concern has been with describing what happens at given places in the course of time. But recently interest has turned more and more to describing what happens to given parcels of water in the course of time. There is a switch from a spatial to a material description. The progress of a parcel along its path can be calculated from

$$t - t_o = \int_{s_o}^{s} v^{-1}\, ds, \qquad (1)$$

where $t - t_o$ is the time it takes for a parcel to travel from s_o to s, and v is the speed along its path. The speed (v) can, in principle, be determined by solving the appropriate flow equation.

The second objective has many aspects

- -- to determine the change in the concentration of a parcel of water due to evaporation at or near the soil surface and due to selective uptake of water by plant roots;

- -- to determine the gain or loss of solutes by parcels of water as a result of diffusive and dispersive mixing with their surroundings;

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- to determine the retardation of solutes relative to the water resulting from adsorption;

- to determine whether solutes precipitate or dissolve.

A large body of experience (theory and experiments) deals with all these factors, although usually only one at a time. In the absence of adsorption, precipitation, and dissolution, combining the flow equation for the solutes with the balance of mass for the water gives:

$$\frac{\partial c}{\partial t} + v \frac{\partial c}{\partial z} = \left.\frac{\partial c}{\partial t}\right|_{\text{parcel of water}}$$

$$= \nabla \cdot D\nabla c + \frac{\beta T}{\theta} c, \qquad (2)$$

where c is the solute concentration, t and v are as before, z is the depth, D is the diffusion/dispersion coefficient, θ is the volumetric water content, T is the rate of transpiration, and β is the spatial distribution function for the volumetric rate of water uptake. On the left-hand side of (2) appears the material time derivative, i.e., the time derivative following the motion of a parcel of water. The last term on the right-hand side of (2) shows that the rate of increase of the concentration due to selective uptake is proportional to the rate of uptake βT, the current concentration c of the parcel of water, and the dryness θ^{-1}. The dependence on θ^{-1} is important in comparing sands, loams, and clays.

I will illustrate the use of equations (1) and (2) for describing the transport of solutes across the root zone and from the water table to drains and ditches.

THE ROOT ZONE

Within the root zone, the velocity at depth z is on the average given by

$$v = \theta v/\theta = \{I - E - T \int_0^z \beta \, dz\}/\theta, \qquad (3)$$

where θv is the volumetric flux at depth z, I is the rate of irrigation, E is the rate of evaporation, and T times the integral of β represents the cumulative rate of uptake above depth z. For constant, frequent irrigation and constant E and T, this equation tends to become true at each instant.

Figure 1 shows depth-time trajectories of parcels of water when the rate of uptake decreases exponentially with depth, [$\beta = \delta^{-1} \exp(-z/\delta)$, where δ can be interpreted as a characteristic length for the rooting depth] for different leaching fractions $L = (I - E - T)/I$. The difference between these trajectories is most pronounced below the root zone: if L is large, the water moves more rapidly. The trajectories provide a measure for the response time of the root zone to changes in irrigation management.

If exclusion of solutes by plant roots is the main cause of change in concentration of parcels of water, then integration of (2) shows that this concentration changes according to

$$c_{\text{parcel of water}} = c_I \exp \int_{t_o}^{t} (\beta T/\theta)\, dt$$

$$= c_I \exp \int_0^z \beta T/(\theta v)\, dz, \qquad (4)$$

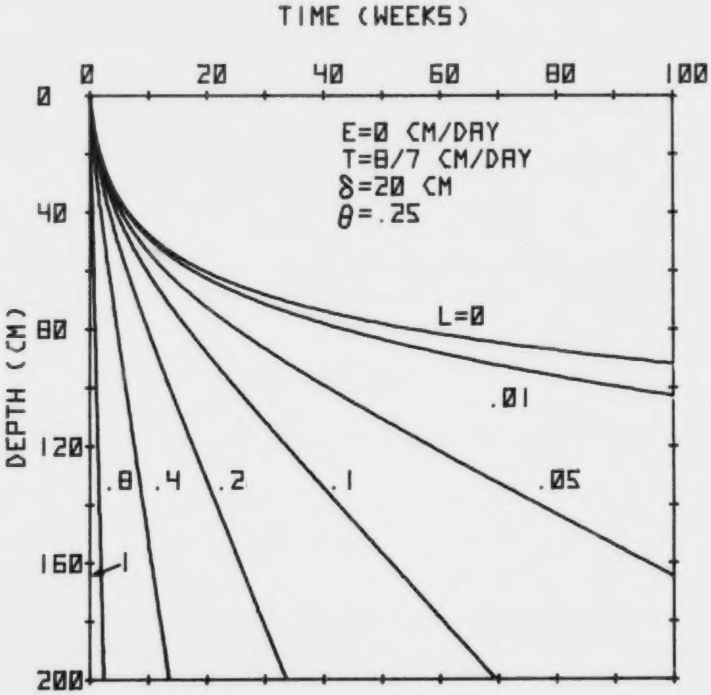

Figure 1. Depth-time trajectories of parcels of water.

where c_I is the concentration of the irrigation water (after correcting for E). This equation applies always, but it is easiest to implement if βT and v are fixed functions of position and time, i.e., if the flow is steady. Following the change in concentration of a parcel of water along its depth-time trajectory allows one to determine the resulting steady (Raats, 1974a,b) and unsteady (Raats, 1975) salinity profiles. If the first term on the right-hand side of (2) describing diffusion and dispersion is retained (assuming D = constant), then the steady salinity profile is given by

$$c/c_I = (I\delta/D) \exp \lambda \int_{z/\delta}^{\infty} \exp -\lambda \; dz/\delta, \qquad (5)$$

where

$$\lambda = (I\delta/D) \; [L \; z/\delta + (1 - L) \exp - z/\delta]. \qquad (6)$$

In view of the small velocity of the water and the uniform distribution of the water content, the assumption that D is constant seems reasonable. Equations (5) and (6) imply that for a given rooting depth, δ, and leaching fraction, L, the solute distribution is a unique function of the Peclet number $I\delta/D$. For a given value of the leaching fraction, the Peclet number is a measure of the relative importance of convective and diffusive transports. Figure 2 shows the salinity profiles for

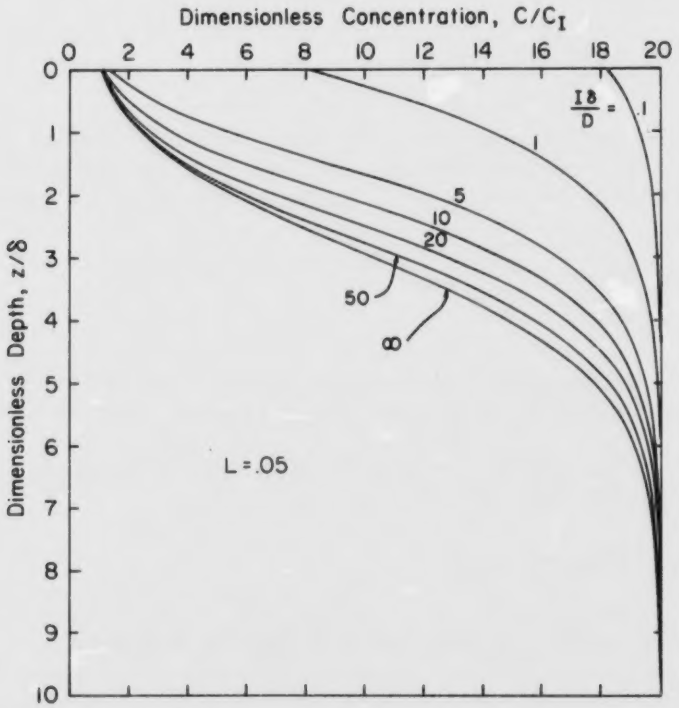

Fig. 2. Effect of diffusion and dispersion on steady salinity profiles.

$L = 0.05$. For $I = 1$ cm/day, $\delta = 20$ cm and $D = 1$ cm^2/day, the Peclet number $I\delta/D = 20$ and the effect of dispersion is noticeable. For $L = 0.01$, it would be dominant in the lower part of the root zone. For $L = 0.2$, it would be negligible. For a given value of L, the influence of upward diffusion and hydrodynamic dispersion will be largest during the winter when I is small. Of course, if I is small, it is less crucial to keep L small.

With infrequent irrigation, the situation is more complex (Rawlins and Raats, 1975). Periods of predominant infiltration, redistribution, and evaporation plus uptake alternate. Near the end of an extraction period, the entire root zone tends to approach a uniform total potential with the osmotic potential dominant in the lower part of the root zone (Wadleigh, Gauch, and Strong, 1947). Each irrigation largely obliterates the matric component of the stress, and displaces the saline water further downward. One can do a reasonable job of describing the events if the hydraulic properties of the soil and the amount and quality of irrigation water are known (Rhoades and Merrill, 1975).

TRANSPORT TO DRAINS AND DITCHES

The unidirectional Dupuit model provides the simplest basis for estimating travel times. The key assumption is that at any distance (x) from the drainage facility, the horizontal component of the velocity is uniform over any vertical cross section. If the efflux is at $x = 0$ and the velocity is zero at $x = X$, then the velocity at any x is given by:

$$v = -(\theta A)^{-1} \int_x^X f \, dx, \tag{7}$$

where A is the cross-sectional area at x, and f is the rate of input per unit distance in the x-direction. Introducing (7) into (1) gives the general expression for the transit time from $x = x_o$ to $x = 0$:

$$\tau = \int_0^{x_o} \theta A \left\{ \int_x^X f \, dx \right\}^{-1} dx. \tag{8}$$

The transit time depends on the distribution of θ and A between 0 and x_o, and on the distribution of f over the entire interval 0 to X.

If θ, A (taken equal to depth Y times unit thickness), and f are constant, then (8) reduces to

$$\tau = -\bar{\tau} \,\ell n\, (1 - q), \tag{9}$$

where $\bar{\tau} = \theta A/f$ and $q = x_o/X$. Solving (9) for q gives

$$q = 1 - \exp -\tau/\bar{\tau}. \tag{10}$$

Differentiation of (10) with respect to θ gives

$$dq/d\tau = \bar{\tau}^{-1} \exp - \tau/\bar{\tau}. \qquad (11)$$

The time $\bar{\tau}$ is equal to the volume of the water in the system, θAX, divided by the rate of input, fX, and may be regarded as the turnover time of the system. The dimensionless distance q may be interpreted as the cumulative transit time density distribution function of the system. The output resulting from a step change of the solute concentration in the input will correspond to q. The derivative $dq/d\tau$ may be interpreted as the transit time density distribution or transfer function of the system. The output resulting from a pulse input of solute will correspond to $dq/d\tau$. A uniform periodic input of solute with amplitude a_o and frequency Ω will produce an output with amplitude a and phase shift b given by (cf., Raats, 1977. Appendix)

$$a = a_o\ (1 + \Omega^2\ \bar{\tau}^2)^{-1/2}, \qquad (12)$$

$$b = \tan^{-1} \Omega\ \bar{\tau}. \qquad (13)$$

If $\theta = 0.4$, $Y = 10$ m, and $q = 0.5$ m/yr then $\bar{\tau} = 8$ yr. If the input of the water is distributed uniformly over the year, then for annual variations of the input of salinity, the amplitude of the output is about one-eighth of that of the input, and the phase shift is 82.9°, or nearly 3 months.

The expressions for τ, q, and $dq/d\tau$ given by equations (7) to (9) are identical to the well-known transit-time density distribution of a well-mixed system of volume θAX and rate of input fX. Without giving much justification, the model has been used in theoretical discussions of input/output relationships and in attempts to fit experimental data. Elsewhere, I have shown, on the basis of Laplace's equation, that the well-mixed model implied in (9) to (11) is exact if the efflux at $x = X$ is uniformly distributed over the vertical (Raats, 1977, Appendix). If the drains or ditches are widely spaced relative to the depth of the first impermeable layer then the influence of the details of the flow near the drains or ditches will be small. Adapting results from Jury (1975), I have shown elsewhere that for a uniform input at the water table and output into a drain located at the water table, the well-mixed model is a satisfactory approximation for spacing-depth ratios larger than 10.

A diagram of q versus τ can be used to summarize the displacement process for a given geometry and for given boundary conditions (Fig. 3). Times τ_b, τ, and τ_m are the breakthrough, turnover, and memory times, respectively. The area above the curve b d e corresponds to the total amount of water in the system. The area a c f g corresponds to the total amount of water applied at time τ. This water is divided in three parts: water that has bypassed (b c d), water present in completely leached stream tubes (a b d h), and water present in partially leached stream tubes (h d f g). The area d e f represents water yet to be

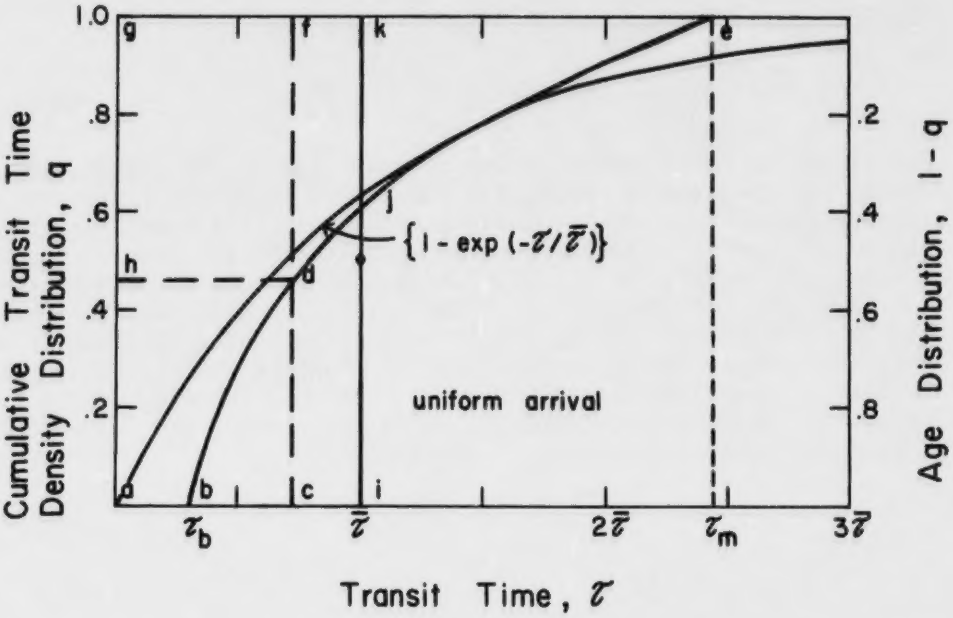

Figure 3. Comparison of exact and approximate transit-time density distributions for uniform input at the water table and output into a drain located at the water table.

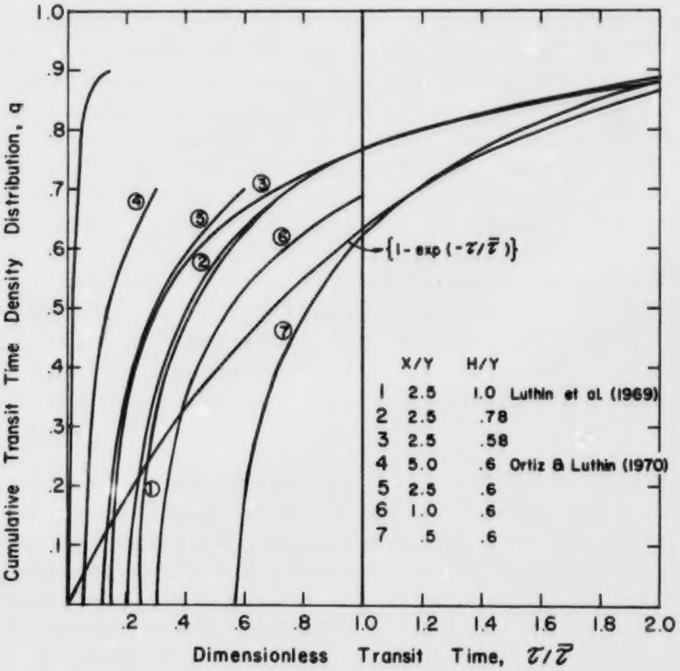

Figure 4. Integral properties of leaching processes.

displaced from the partially leached stream tubes. At the turnover time, $\bar{\tau}$, this area is equal to the area representing bypass.

Figure 4 shows calculated q versus $\tau/\bar{\tau}$ curves for ponded leaching and for seven different combinations of half spacing-depth ratios X/Y and drain depth-depth ratios H/Y (Luthin et al., 1969; Ortiz and Luthin, 1970). The exponential distribution is also shown. Narrow spacings and large drain depths result in large breakthrough times. Curves 4 to 7 were actually determined for anisotropic systems with the same half spacing-depth ratio, but different ratios of the principal hydraulic conductivities in the horizontal and the vertical directions.

CONCLUDING REMARKS

Most discussions of movement of water in soils adopt the spatial point of view, i.e., they describe what happens at given places in the course of time. This is quite satisfactory if the primary interest is in the state and movement of water, but moving water is also a vehicle for the transport of solutes. This aspect can be best dealt with by adopting the material point of view, i.e., by describing what happens in the course of time to given parcels of water. I have used this approach to describe transient salinity profiles in the root zone and multidimensional, steady flows (see Raats, 1975, 1977). The concepts being developed are applicable to a wide variety of water management problems: leaching of saline soils, development of saline seeps, appearance of salts, nutrients, and pesticides in streams, ditches, and tile lines; movement of water bodies injected in aquifers; the use of temperature and radioactive substances as tracers in hydrology.

REFERENCES

Jury, W. A. 1975. Solute travel-time estimates for tile-drained fields. I. Theory. Soil Sci. Soc. Amer. Proc. 39:1020-1024.

Luthin, J. N., P. Fernandez, B. Maslov, J. Waerner, and F. Robinson. 1969. Displacement front under ponded leaching. J. Irrigation and Drainage Div., Amer. Soc. Civil Eng. 95(IR1):117-125.

Ortiz, J., and J. N. Luthin. 1970. Movement of salts in ponded anisotropic soils. J. Irrigation and Drainage Division, Amer. Soc. Civil Eng. 96(IR3):257-264.

Raats, P. A. C. 1974a. Movement of water and salts under high frequency irrigation. Proc., 2nd Intl. Drip Irrig. Congress, San Diego, CA. pp. 222-227.

Raats, P. A. C. 1974b. Steady flows of water and salt in uniform soil profiles with plant roots. Soil Sci. Soc. Amer. Proc. 38: 717-722.

Raats, P. A. C. 1975. Distribution of salts in the root zone. Journal of Hydrology 27:237-248.

Raats, P. A. C. 1977. Convective transport of solutes by steady flows. Agricultural Water Management (in preparation).

Rawlins, S. L., and P. A. C. Raats. 1975. Prospects for high frequency irrigation. Science 188:604-610.

Rhoades, J. D., and S. D. Merrill. 1975. Assessing the suitability of water for irrigation: Theoretical and empirical approaches. Proc., Expert Consultation on Prognosis of Salinity and Alkalinity, Rome, Italy, June 1975.

Wadleigh, C. H., H. G. Gauch, and D. G. Strong. 1947. Root penetration and moisture extraction in saline soil by crop plants. Soil Sci. 63:341-349.

MODELS FOR PREDICTING THE IMPACT OF IRRIGATION ON SOIL SALINITY

E. Bresler [1]

INTRODUCTION

Soil salinity is an important factor of the environment in which plants grow. Salinity problems are known to exist in many soils throughout the world, particularly in arid and semi-arid regions, where irrigation is necessary for successful agriculture. In irrigated lands, the concentration and composition of the soil solution are derived from the salinity of the irrigation water. The salt concentration of the soil solution is generally greater than the concentration of the irrigation water, as water evaporates into the air and plants extract water from the soil for growth, both of which processes concentrate the salt in the soil solution. Thus, even with relatively good quality water the permanent irrigation practice causes the irrigated soil to be affected by excess soluble salts and to be subjected to the deleterious effect of adsorbed sodium on the physical properties of the soil. Moreover, world prospects indicate that the quality of the irrigation water tends to deteriorate, so that it becomes necessary to utilize water of even poorer quality for irrigation. Reclaiming of saline and sodic soils by proper management is therefore necessary for preservation of agricultural soils and preventing transformation of highly productive soils into non-productive salt-affected soils.

Prediction of salinization and sodication for irrigated soils is important in establishing management practices directed toward reclamation of saline soils already affected by improper management and maintenance or improvement of non-saline or reclaimed irrigated soils. This paper presents a summary of a number of original research studies rather than a specific research report or comprehensive review.

DYNAMICS OF WATER AND SALTS IN IRRIGATED SOILS

Water-soluble salts entering the soil profile through the process of irrigation may accumulate in the root zone or may be leached out of this zone, depending on the convective diffusive transport processes and solute interactions within the soil.

In general, the macroscopic rate at which a given solute moves in the soil system depends on the average flow pattern, on the rate of molecular diffusion, on the rate of adsorption-desorption, and on the ability of the porous material to spread the solute as a result of local macroscopic deviations from the average flow. For proper modeling and prediction of the manner of solute transport in a natural soil profile, these phenomena must be considered simultaneously. In dealing with the problem of simultaneous transfer of solute and water, one usually assumes that the transport of the solute is governed by convection (viscous movement of the soil solution) and diffusion (thermal motion within the soil solution), and that water flow is governed by Darcy-type water flow equations.

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Governing Water and Salt Flow Equations

In agricultural soils, changes in water content due to infiltration, redistribution, evaporation, and transpiration bring about the simultaneous movement of water and salt. Steady state flow conditions occur very seldom under natural conditions. A mathematical expression for one-dimensional transient flow conditions is derived from a consideration of continuity, or mass conservation. This states that the rate of change of mass (solute or water) within a given soil element must be equal to the difference between the amounts of mass that enter and leave the element. By equating the difference between outflow and inflow to the amount of mass that has accumulated in the soil element, and considering the case of one-dimensional vertical flow, one obtains the expressions (1) and (2) for flows of solute and water, respectively.

The flow of salt is described by:

$$\frac{\partial}{\partial t}(Q + \theta c) = \frac{\partial}{\partial z}\left[D(V,\theta)\frac{\partial c}{\partial z}\right] - \frac{\partial (qc)}{\partial z} + S' \qquad (1)$$

where

Q,	local concentration (positive or negative) of solute in the 'adsorbed' phase (meq/cm^3 soil), usually depends on both θ and c;
θ,	volumetric water content of the soil (cm^3/cm^3);
c,	concentration in the solution phase (meq/cm^3 soil solution);
S',	any sink or source rate term due to salt uptake, production, precipitation, or dissolution (meq cm^{-3} sec^{-1});
t,	time;
z,	vertical space coordinate (considered to be positive downward);
D,	combined diffusion-dispersion coefficient (cm^2 sec^{-1}), a function of V and θ;
q,	volumetric specific flux of solution (cm^3 cm^{-2} sec^{-1});
V,	average interstitial flow velocity (cm sec^{-1}).

The one-dimensional vertical flow of water in an incompressible unsaturated soil with water uptake by plant roots can be described by:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial H}{\partial z} - \frac{\sigma}{\rho g}\frac{\partial \pi}{\partial z}\right)\right] - S(z,t) \qquad (2)$$

where:

K,	hydraulic conductivity of the soil (cm $\sec^{-1}$), a function of θ, c, and ionic composition;
H,	hydraulic head (sum of suction head h and gravity head);
σ,	osmotic efficiency coefficient;
ρ,	solution density;
π,	osmotic pressure, a function of c as given by Van't Hoff's Law;
S,	water uptake by roots (cm^3 H_2O cm^{-3} soil), considered positive from the soil into the roots.

As a result of the lack of physical understanding of flow within the plant itself there has been a tendency to describe water uptake by macroscopic equations which assume that the rate of uptake is proportional to soil hydraulic conductivity K and to the difference between the root suction (h_r) and the total soil suction $h + \pi$.

Boundary Conditions

Equations (1) and (2) must by supplemented by appropriate initial and boundary conditions. When salinization and reclamation are considered, the initial conditions are simply the predetermined distribution in the soil of solution concentration (c), water content (θ), and water suction (h) prior to any salinization or reclamation process.

The lower geometric boundary Z may be chosen as the groundwater table depth or any arbitrary depth always below the wetting front. The boundary conditions at this depth Z at any time ($t \geq 0$) are given by a constant solution concentration, constant suction head, or zero values of both solution concentration and suction head gradients.

Along soil-air interfaces (in the absence of ponding) the soil can lose water to the atmosphere by evaporation or gain water by infiltration. While the potential (*i.e.*, maximum possible) rate of evaporation from a given soil depends on atmospheric conditions only, the actual flux across the soil surface is limited by the ability of the porous medium to transmit water from below. Similarly, if the potential rate of infiltration (*e.g.*, the rain or irrigation intensity) exceeds the infiltration capacity of the soil, some of the water may be lost by surface runoff. Here, again, the potential rate of infiltration is controlled by atmospheric or other external conditions, whereas the actual flux depends on antecedent moisture conditions in the soil. Thus, the exact boundary conditions to be assigned for water flow at the soil surface ($z = 0$) cannot be predicted *a priori*, and a solution must be sought by maximizing the absolute value of the water flux (while maintaining the correct sign) subject to the above-mentioned requirements and restrictions of θ or h. For solute, the soil surface boundary conditions that must be satisfied are expressed by the fact that the amount of salt entering the soil profile in unit time by the irrigation water must be equal to the inflow flux of water at the soil surface (q_o) times the salt concentration of the irrigation water (C_o). This is true as long as water infiltrates into the soil during irrigation. However, during evaporation, or the water extraction period (evapotranspiration period), the solute flux across the soil surface must be zero if salt uptake by plants is neglected.

PREDICTION OF ACCUMULATION, LEACHING, AND DISTRIBUTION OF SALTS IN SOILS

Procedures for estimating the distribution of salt in depth and time, which will be described here, are applicable to most salinity situations when the effect of irrigation is considered. The procedures include prediction of total salt concentration when neither salt precipitation nor uptake by plants take place (S' of eq. (1) is dropped). The procedure may also be useful to predict a specific ion distribution when its exclusion or adsorption is taken into consideration or being ignored.

The problem is defined by the nonlinear partial differential equations (1) and (2), with the boundary conditions noted, and at present, can be solved by numerical methods only with the aid of a computer. Solution to many applied specific cases may be obtained (e.g., Hanks, Klute, and Bresler, 1969; Bresler and Hanks, 1969; Bresler 1973a,b; Neuman, Feddes, and Bresler, 1975). These methods of solution resulted in a numerical technique that nicely combines explicit-like efficiency, unconditional stability, and second-order accuracy.

Fallow (no vegetation) Isothermal Conditions

1. Noninteracting solute -- In this case the solute is assumed to be inert with respect to its environment, so that interaction with the soil matrix is ignored and therefore the effect of salt fluctuation on water flow, adsorption, exclusion, and gravity segregation effects are neglected. From the point of view of man-made soil salinization and reclamation this prediction is restricted to the case of total salt concentration when neither salt precipitation nor dissolution takes place. This may also be a good approximation for anions (such as chlorides) under a wide range of natural conditions where precipitation of carbonate and sulfate minerals in the soil (Oster and Rhoades, 1974), which may decrease the salt burden of drainage water, are irrelevant.

Under these conditions the governing equation for transient vertical diffusive convective flow of an inert solute under isothermal conditions is eq. (1) with zero values for Q and S'. Similarly, the differential equation that governs vertical solution (water) flow in this soil is eq. (2) with both S and σ having a value of zero and $K = K(\theta)$, a unique function of θ. As mentioned before, numerical methods must be used to solve these differential equations subjected to the pertinent boundary conditions. A finite difference solution is given by Hanks et al. (1969) to calculate the values of $\theta(z,t)$, $h(z,t)$, and $q(z,t)$ for the processes of infiltration, redistribution, drainage, and evaporation. The calculated values can then be used to obtain $c(z,t)$ from eq. (1).

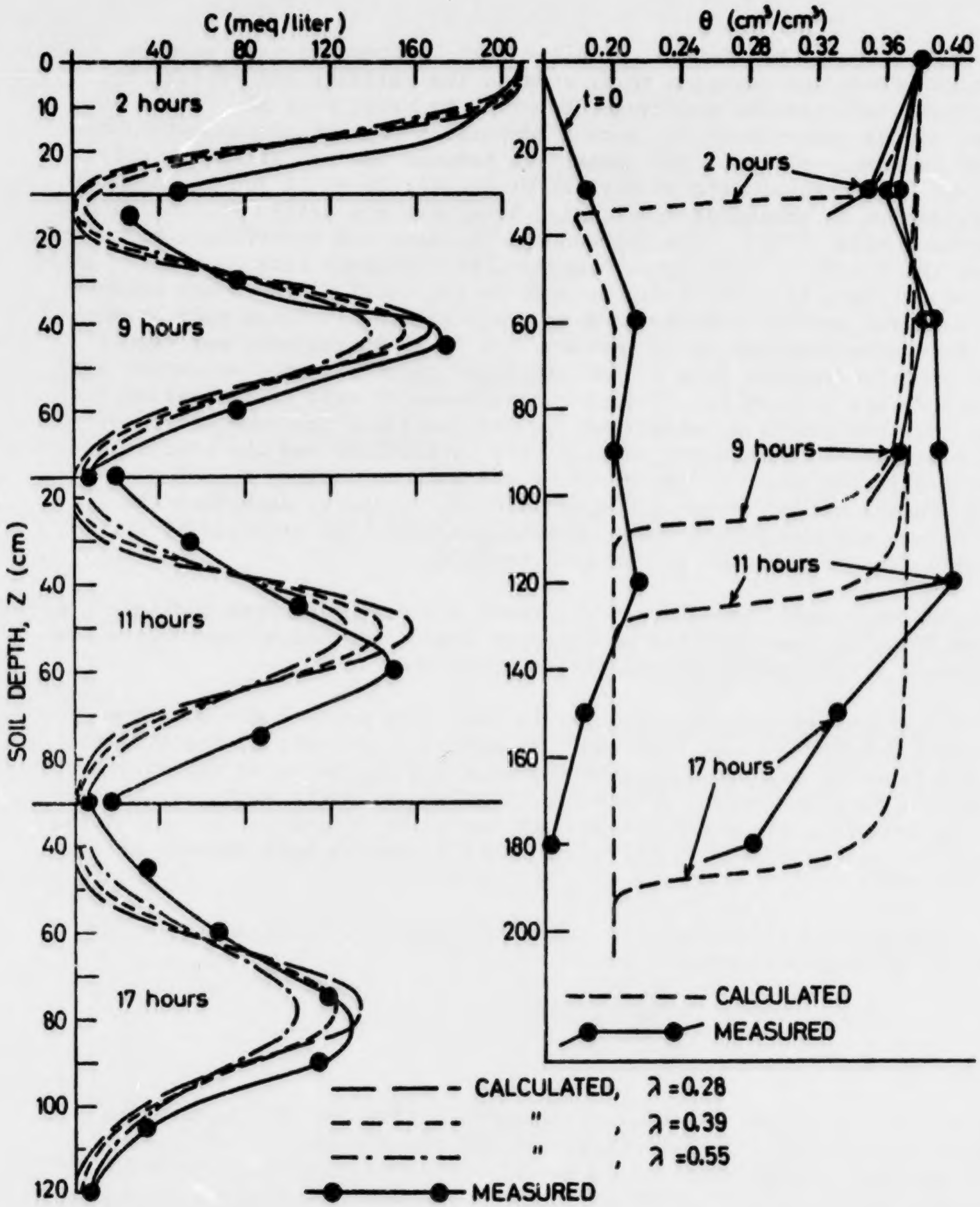

Fig. 1: Field distribution of chloride and water [Warrick et al., 1971, figures 5, 6, and 8] (solid line connecting the black circles), compared with predicted profiles (dashed lines) for four infiltration times and three values of dispersivity λ. (After Bresler, 1973a.)

Any estimation or prediction technique must be compared with experimental results before one can gain confidence in its validity and reliability. The field infiltration experiment reported by Warrick et al. (1971) provides a good opportunity for such a comparison in salt concentration and water content profiles. The comparison between the calculated results and the experimental data of Warrick et al. for 2, 9, 11 and 17 hours of infiltration is presented in Fig. 1. Note that the origin ($z = 0$) on the left-hand side of Fig. 1 is shifted and the data are accordingly translated along the z axis to distinguish between the different sets of times. Also note that there is a small discrepancy in the total salt balance between the measured and the calculated data. Since the calculated salt balance in the system appeared to be correct, the small discrepancy may result from minor deviations from the assumptions. However, good agreement generally exists between the calculated and measured salt concentration and water content profiles, especially if one considers the homogeneity of the soil profile with depth and also the variability and the precision involved in the measurements of water and salt in soils. Fig. 1 also shows that a narrow range of dispersivity (λ) properly describes the field data and the proper value of λ is generally not affected by infiltration time or position in the soil profile.

The good agreement between the calculated and measured water and salt profiles (Fig. 1) suggests that macroscopic scale theoretical approaches are generally satisfactory for prediction purposes.

2. Solute interacting with soil -- To take into account the physicochemical interactions between the ions and the soil matrix, the effects on the flows of osmotic gradients and of anion exclusion or cation adsorption must be considered. Here the prediction procedure must use the governing equations (1) and (2) with zero value for S' and S. In evaluating the value of $Q = Q(c,\theta)$ in (1) a distinction must be made between anions and cations.

a) Cations -- For cations, the value of $Q(\theta,c)$ is always positive ($Q > 0$) and can be estimated from:

$$\frac{\bar{x}_{Na}}{\bar{x}_{Ca}} = 0.0158 \frac{(Na)}{\sqrt{Ca + Mg}} \qquad (3)$$

where $\bar{x}$ is equivalent fraction of adsorbed cation and the parentheses denote the concentration of the cations in the solution in mmol/liter. This equation states that the cation of higher valency is preferentially adsorbed by the clay fraction of the soil and that the preference increases with the dilution of the soil solution. Magdoff and Bresler (1973) used an equation similar to (3) to predict the distribution of exchangeable sodium percentage in sodic soil (ESP = 22) irrigated with water containing various concentrations of $CaCl_2$ in order to reclaim the soil. They then used these predicted results (Fig. 2) to evaluate various methods for reclamation of sodic soils by $CaCl_2$ solutions. They concluded that the prediction procedure is able to distinguish between treatments and rank them in the same order of efficiency of Na replacement by Ca as the experi-

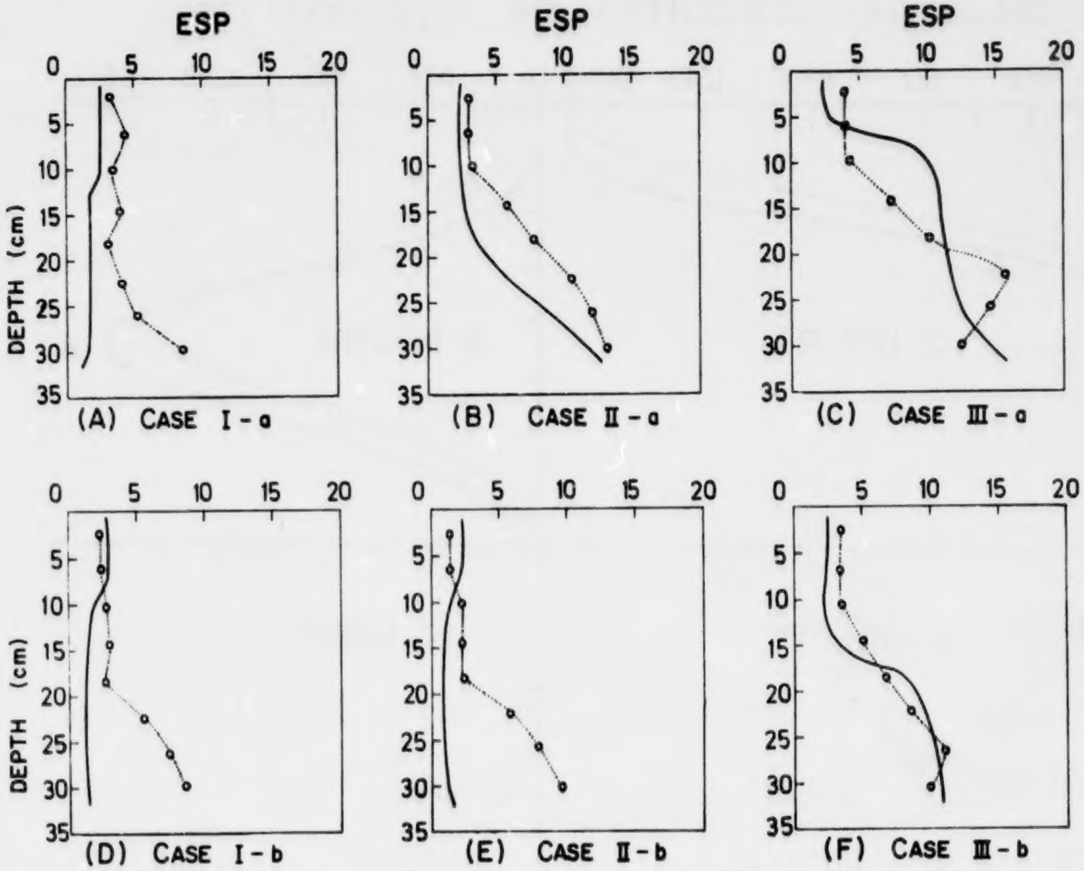

Figure 2. Experimental (circles connected by dots) and predicted (solid lines) distribution of exchangeable sodium percentage (ESP). (After Magdoff and Bresler, 1973).

mental results. In some cases there was a fairly good quantitative agreement between calculated and experimental ESP profiles (Fig. 2). Thus, even with the simple assumption underlying it, the procedure was found to be sufficiently good for screening and general prediction purposes.

b) Anions -- For anions the value of $Q(c,\theta)$ is always negative ($Q < 0$) due to anion exclusion from the negatively charged soil particles. When local equilibrium between the soil solution phase and the exchange phase can be assumed, the amount of excluded anions per cm^3 of the soil may be estimated from Bresler (1973b):

$$Q(c,\theta) = \Gamma_{-}(\theta,c) \cdot A_{ex} \cdot \rho_b = \theta_{ex}(\theta,c) \cdot c. \qquad (4)$$

Here Γ_{-} (meq/cm^2) is the calculated negative adsorption (a function of θ and c), A_{ex} (cm^2/g) is the specific exclusion surface area of the soil (Edwards, Posner, and Quirk, 1965), ρ_b (g/cm^3) is the bulk density of the soil, and θ_{ex} is the volume of anion-free solution per unit volume of the soil (cm^3/cm^3). The value of $Q(c,\theta)$ may be obtained by experimentation or may be estimated from eq. (4).

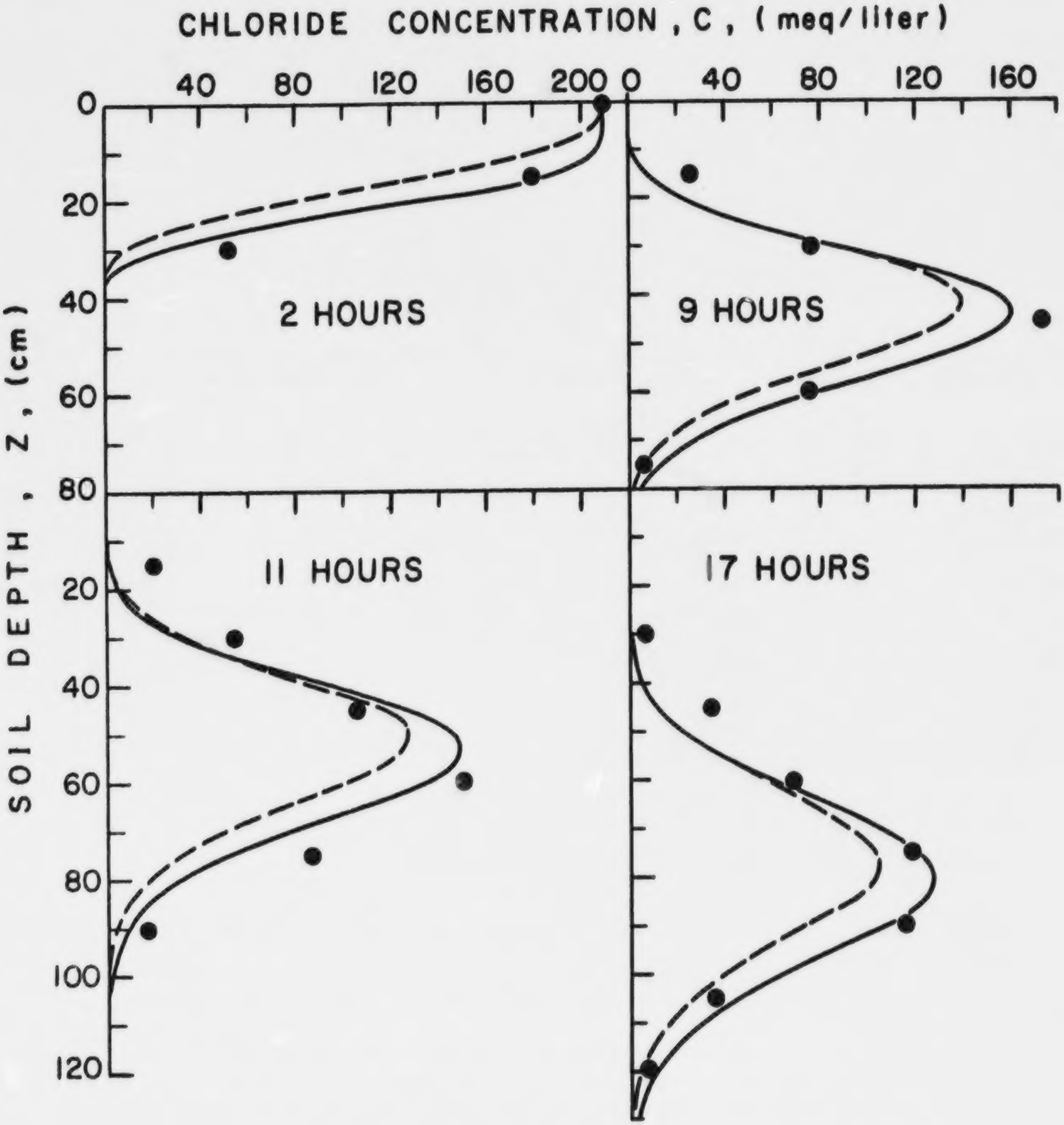

Fig. 3: Predicted chloride distribution (continuous lines) as compared with the field data (black circles) of Warrick et al. (1971) for four infiltration times. Dashed lines denote data of Fig. 1 for noninteracting solute with λ = 0.55, solid lines denote predicted results in which anion exclusion was considered. (After Bresler, 1973b.)

The irrigation experiment conducted in the field by Warrick et al. (1971) enables us also to evaluate the effect of possible interactions between anions and the soil matrix on the prediction of accumulation and leaching of salts in soils. Such interactions are considered by Bresler (1973b) by including data on $\sigma(\theta,c)$ and on $Q(\theta,c)$ in the numerical solution to the governing equations (1) and (2). A comparison between calculated results and the data of Warrick et al. for 2, 9, 11 and 17 hours of infiltration using a dispersivity value of $\lambda = 0.55$ is given in Fig. 3. Some slight improvement in the agreement between the predicted results and the measured chloride distribution data can be seen.

In analyzing the effect of ion-soil interaction, it appears that salt concentration gradients were not an important factor in the movement of the soil solution. On the average over the whole flow system the osmotic part of the flow was calculated to be less that 5% of the total solution flow. It appears, therefore, that the slight difference between the two predicted lines shown in Fig. 3 may be a consequence of the effect of anion exclusion and not of σ on the flow.

The effect of anion exclusion on the rate of chloride movement in the soil may explain part of the small discrepancy in total salt balance between measured and calculated data which was noted in Fig. 1. However, only about 10% of the chlorides in the profile were excluded, and, therefore, the agreement between the estimated and the measured data is only slightly improved.

Crop-growing Conditions

The assumption that salt uptake by plants might be neglected could also be applied in the presence of plants. However, water uptake by plants is a dominant factor and must be considered when salt distribution under crop-growing conditions is of interest. Under these conditions, a non-zero macroscopic water extraction term must be introduced in eq. (2) to account for water loss due to transpiration.

Introducing either an empirical or a theoretical extraction term into (2) and solving it numerically subject to the boundary conditions (Neuman et al., 1975), makes it possible to estimate the salt distribution as before from the solution of (1). The degree of accuracy that one obtains with this approach in predicting the soil salinity variables, $c(z,t)$, $\theta(z,t)$ and $h(z,t)$, depends primarily on the following factors: (a) proper choice of the mathematical model to give an adequate description of the physical system at hand; (b) proper specification of boundary conditions; (c) accuracy and stability of the numerical procedure; and (d) accuracy of the soil and plant parameters used in the computation. Of these factors, the most critical one is the last.

Because of the difficulties involved in obtaining all the necessary soil-water-plant-salt parameters required to estimate the salt distribution by these abovementioned methods, a simplified prediction procedure seems to be of practical usefulness. Such a simplified procedure to estimate salt distribution in the soil profile under crop-growing field conditions was described by Bresler (1967). The method is essentially a numerical solution of the mass balance equation (1) when $D(\theta,V) = 0$, $S' = 0$ and the time increment Δt was set equal to the time interval between two successive water applications j and $j-1$. Furthermore, only the downward flow was considered and was assumed to take place in the range of water content ($\bar{\theta}$) between saturation and the assumed "field capacity" of the soil. In addition, the amount of water passing any soil depth $z \neq 0$ in Δt^j was estimated by the difference between the amount of water applied ($\bar{Q}^j$) and the water consumption by the crop from the soil surface down to the depth z in Δt^{j-1}. With these approximations, the mass balance equation (1) becomes:

$$\bar{Q}^j C_o{}^j - [\bar{Q}^j - \int_o^z E^{j-1}(z)\,dz]\,c^{j-1/2}(z) = \int_o^z [c^j(z) - c^{j-1}(z)]\,\bar{\theta}(z)\,dz \qquad (5)$$

Using finite difference notation in terms of any discrete soil layer i and for any j-th irrigation, the following system of linear equations is obtained from eq. (5):

$$\bar{Q}^j C_o^j - (\bar{Q}^j - \sum_{k=1}^{i} E_k^{j-1})\,\frac{C_i^{j-1} + C_i^j}{2} = \sum_{k=1}^{i} (C_k^j - C_k^{j-1})\,\bar{\theta}_k \qquad (6)$$

Here (eq. 5 and 6) $\bar{Q}$ is the amount of water applied to the soil surface by irrigation (or rain) (cm), j is the index of water applied by irrigation (or rain storm), and E is the amount of water per unit volume of soil (cm^3 H$_2$O/cm^3 soil) consumed by the crop during the time interval Δt^j. Estimation of the salt profile from the solution of eq. (6) is possible if $\bar{\theta}(z)$ and $E(z)^{j-1}$ can be evaluated, provided that the initial salt concentration, the amount of water applied, and its salt concentration are measured. Evaluation of $E^{j-1}(z)$ may be obtained from theories or from the large number of water requirement experiments which have been conducted in many countries (particularly in Israel). Demonstration of the effect of $\bar{\theta}(z)$ on the salt distribution data and on the prediction power of eq. (6) is given in Fig. 4. The applicability of this prediction method was tested by D. Yaron (personal communication) and Yaron et al. (1972), who compared many irrigation experiment data with the calculated results, and found the former to be applicable in many practical cases.

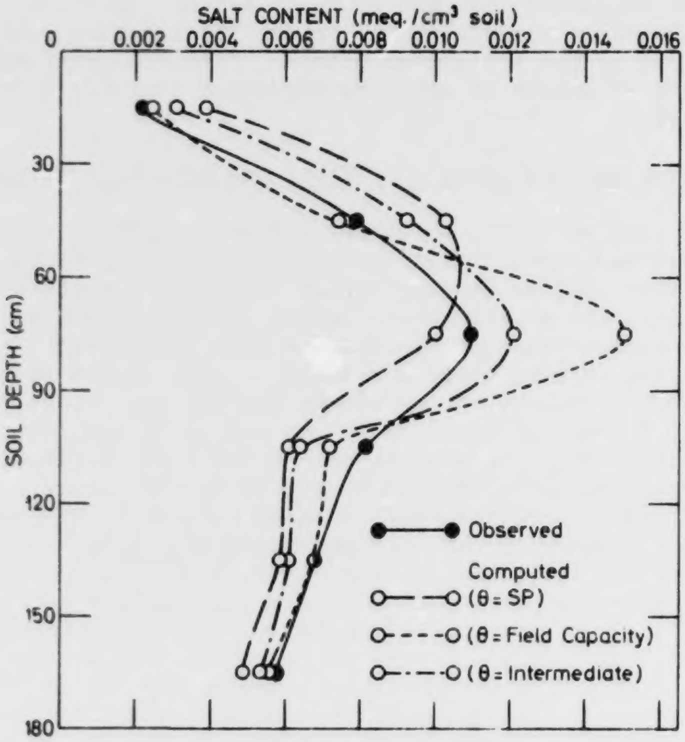

Figure 4. Predicted (computed by eq. (5)), and observed salt distribution data. (After Bresler, 1972).

IRRIGATION METHOD - SOIL SALINIZATION AND RECLAMATION

The problem of irrigation method from the point of view of prediction of soil salinity may have short- or long-run implications. In the short run, the direct effect of seasonal irrigation water on soil salinization within a relatively short time period, is considered. The short-run problems include also irrigations for the reclamation of initially saline soil to optimize the yield of the following crop.

In the long run, the perennial soil salinization effect and possible loss of productive soil must be considered. Usually, the long-run effects are the time integral of the short-run effects. Thus, when the short-run effects can be predicted, it is also possible to predict the long-run effects simply by integrating all the short-period effects over the longer period of interest.

The reclamation process is aimed at removing the salinity limiting factor so that crops will not suffer any yield reduction. Reclamation of saline soil is essentially a process in which the high-concentration soil solution is displaced by a less concentrated solution of the irrigation water. Theoretical results suggested what was found in several laboratory experiments and field trials--that reclaiming saline soil by leaching with irrigation water is affected by the irrigation method. Thus, reclamation of saline soil may be more efficient by applying sprinkler or trickle-drip irrigation methods.

Soil Salinization and Reclamation by Flood and Sprinkler Irrigation

The salt concentration (meq/l solution) and salt content (meq/g soil) profiles in flooded and sprinkler-irrigated soil are demonstrated in Fig. 5. In both irrigation methods the upper part of the soil profile, at the end of the irrigation, has a salt concentration identical to the low concentration of the applied water. The salt profile increases to a maximum value close to the wetting front and drops to its initial value below the wetting depth. Because of the slower wetting rate under sprinkling, the zone of complete leaching at the end of irrigation (infiltration) extends more deeply into the profile than under flood irrigation. From the end of irrigation until the end of redistribution there is a wide distribution of salt concentrations: The salt added by irrigation water and the salt already present in the soil are thoroughly mixed and dispersed along the entire profile. The dispersal zone is narrower in the sprinkler-irrigated soil during redistribution than in the flooded soil. When the soil is subjected to evaporation, flow occurs upward and downward, simultaneously, in different parts of the soil profile. Thus, some salt continues to move down with the redistributed water and, at the same time, salt near the surface moves upward toward the surface, where it accumulates. The amount of salt which moves to the top depends largely on the salt quantity present in that part of the soil which is shallower than the depths from which water flows upward. Thus, only negligibly small amounts of salt move up during evaporation from soil previously irrigated by sprinklers, and none to the region above a depth of 12 cm. In the flooded soil, on the other hand, more salt moves upward and accumulates at the top. The data in Fig. 5 demonstrate the superiority of sprinkler irrigation over flooding, with respect to soil reclamation, when leaching of hazardous salts present in the soil is considered.

Salinization and Reclamation by Trickle-drip Irrigation

Use of the trickle-drip irrigation method for irrigating saline fields with relatively saline water has become quite common in recent years. The success of the surface approach, as opposed to underground application of trickling, is attributed partly to the formation of a low-salt root zone in the vicinity of the trickle source. In this approach the trickle emitter is placed directly on the soil surface, so that the area across which irrigation takes place is small compared with the total soil surface. As a result, one has a case of three-dimensional flow, which differs from the usual one-dimensional flow of flood and sprinkle irrigation, where the area across which flow takes place is identical to the total area of the wetted field. The general pattern of salt distribution in two soils and for two trickle discharge rates is demonstrated in Fig. 6. From this example one can evaluate the applicability of this irrigation method to the reclamation of saline soil by leaching. This leaching process involves the case of low-concentration irrigation water that miscibly displaces

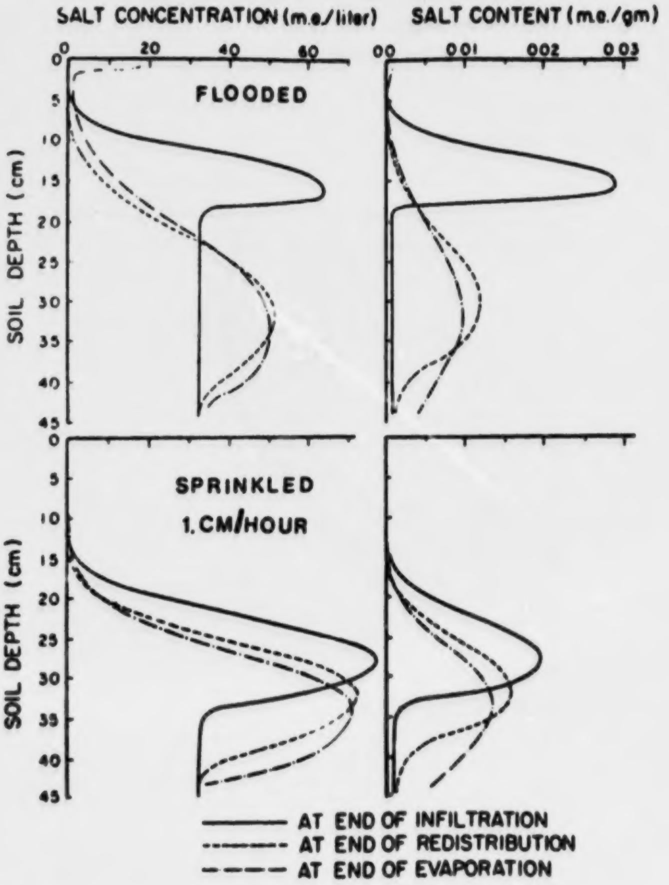

Fig. 5: Prediction of the effect of irrigation method on salt concentration (in the soil solution) and salt content (per gram soil) as a function of soil depth. (Adapted from Bresler and Hanks, 1969.)

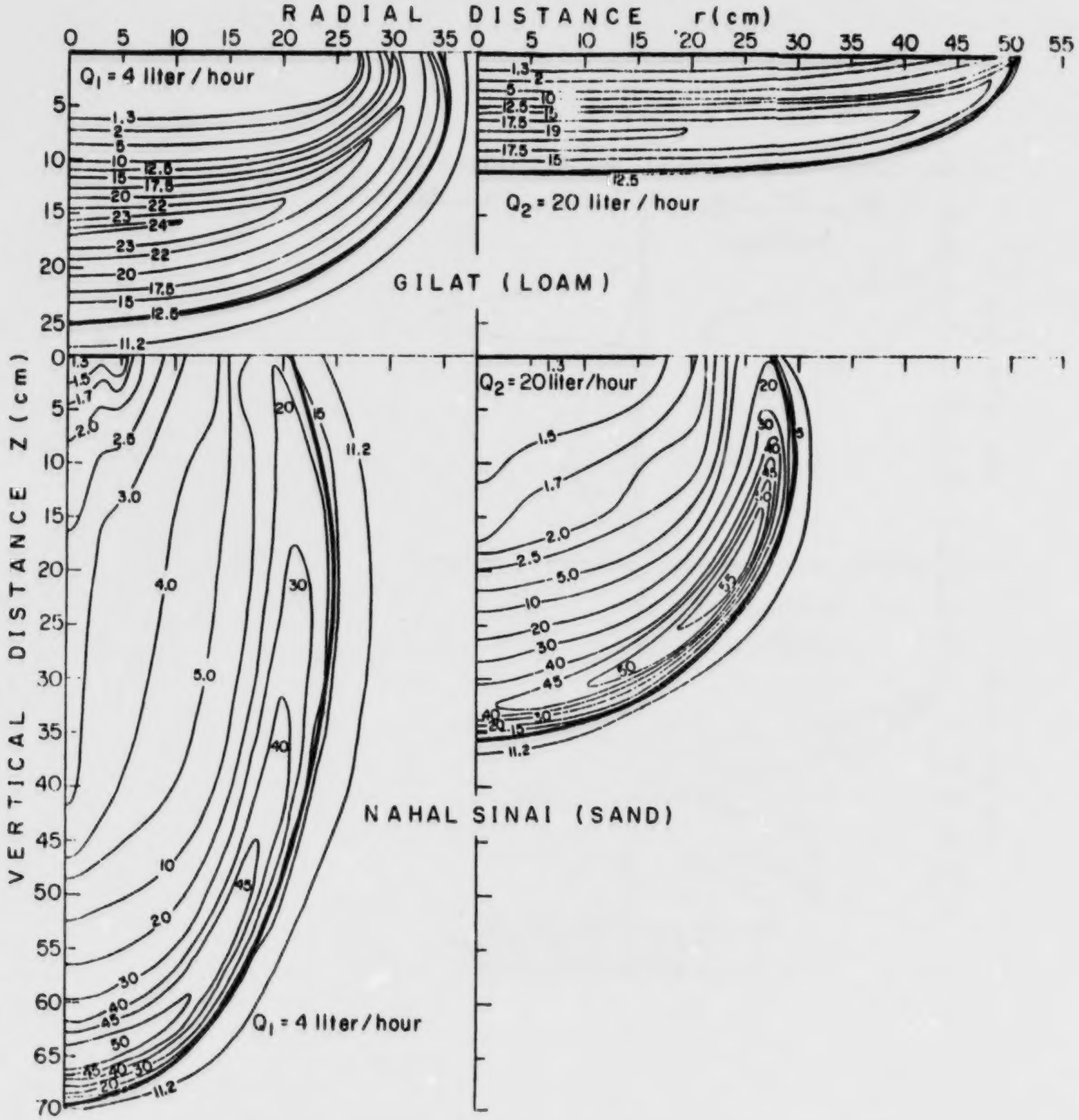

Fig. 6: Volumetric salt content distribution during trickle irrigation for two cases of trickle discharges (Q_1 and Q_2) and two soils (Gilat and Nahal Sinai). The numbers labeling the curves indicate volumetric salt content ($c\theta$) in meq/l bulk soil. (After Bresler, 1975.)

a high-concentration soil solution originally present in the field. Fig. 6 presents the salt content field data in terms of salt content per unit bulk volume of soil (as meq solute/liter bulk soil). It demonstrates the effects of trickle discharge and soil properties on the shape of salt distribution. In both soils and with both discharge rates there is a leached zone close to the position of the emitter, and an accumulation zone close to the wetting front. Here the salt quantities from the leached part of the soil are accumulated and reach a maximum at a certain distance from the irrigation source. The location of this maximum and the accumulation zone is largely dependent of the soil properties and discharge rates of the emitter.

The general pattern of salt distribution and its dependence on initial salinity, salinity of the irrigation water, rate of trickle discharge, and the hydraulic characteristics of the soil, as demonstrated in Fig. 6, is of practical interest for problems connected with water utilization for reclamation of saline soils by irrigation in order to preserve soil productiv-

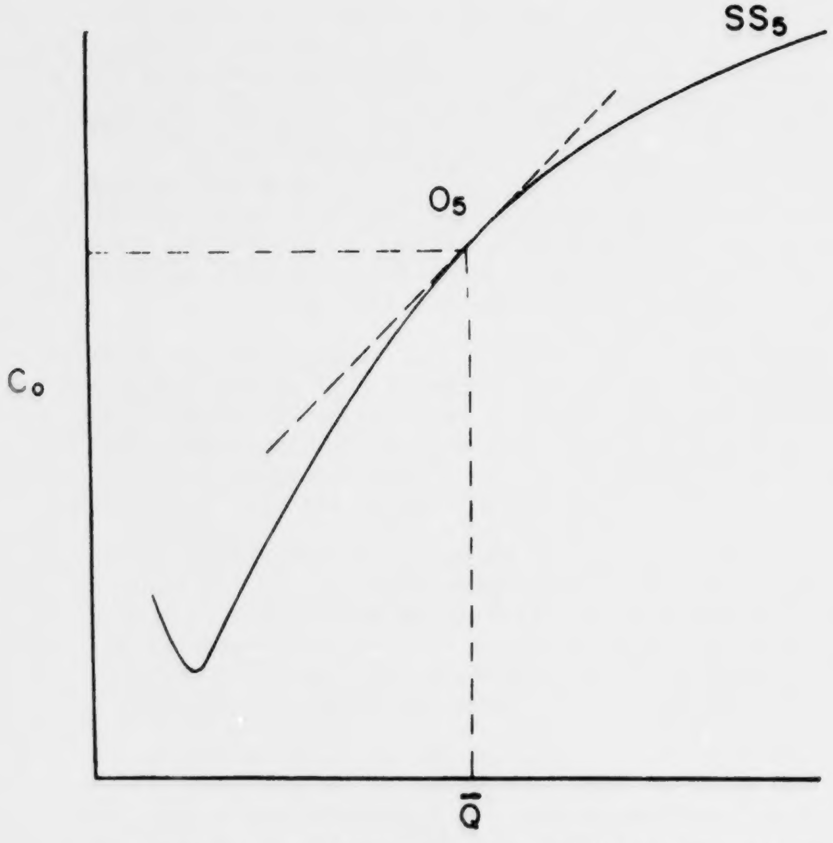

Figure 7. Prediction of the critical iso-soil salinity curve (SS_5) and of the optimal quantity ($\bar{Q}$) - quantity (C_o) combinations.

ity of the root zone. Consider, for instance, a non-productive saline field being irrigated by a set of symmetrical trickle emitters. Suppose that it is important to evaluate the leaching effectiveness of removing salts from a given root volume in which the main plant roots function. With a sufficiently long irrigation duration, depending on soil and on discharge rate, this leached zone may be sufficient for most of the roots to concentrate and function without disturbance. On the other hand, a large quantity of salt may accumulate to an appreciable level at a certain distance from the source close to the wetting fronts (Fig. 6). It is apparent that such a salinization which creates soil limitation to plant growth can be overcome by changing the discharge rate or position of the source, or both.

PREDICTION OF OPTIMAL $\bar{Q}$ - C_o COMBINATION

Equations (1) through (6) together with the appropriate boundary conditions can be applied for purposes of optimization of water quantity and quality in order to preserve productivity of soil resources. The systems of these equations can be classified into four major groups: (a) predetermined functions, such as $K(\theta)$, $h(\theta)$, $D(\theta,V)$, $S(t,z)$, $\sigma(\theta,c)$ and $Q(\theta,c)$; (b) predetermined variables (initial conditions) or pre-reclamation variables $\theta(z,0)$ and $c(z,0)$; (c) man-controlled variables C_o, $\bar{Q}$; and (d) dependent variables, $c(z,t)$, $\theta(z,t)$ and $h(z,t)$. Of particular interest for purposes of optimization is the dependence of $c(z,t)$ and $h(z,t)$ on the man-controlled variables quantity of irrigation water $\bar{Q}$ and water salinity C_o which determine uniquely the salinity regime of the root zone. In other words, optimum control of soil salinity may be obtained by regulating the quantity ($\bar{Q}$) and the salinity (C_o) of the water applied, as well as rate of application, irrigation method, time of application, etc.

The economic problem is to predict the "best" least costly combination of the controllable variables quantity ($\bar{Q}$) and salinity (C_o) of the irrigation water which can ensure that the soil will not lose its productivity, i.e., that a given critical soil salinity index (c_r=SS_i) is not exceeded. The problem is to find the maximum level of C_o and minimum value of $\bar{Q}$ which will not violate the restricted values of c_r=SS_i subject to any set of the finite difference linear form of (1) and (2) such as eq. (6). The formulation consists of a linear objective function to be maximized subject to a set of linear equalities (e.g., eq. (6)), and inequalities (e.g., $c \leq SS_i$). The optimal least-costly combination is illustrated graphically in Fig. 7. The iso-soil salinity curve SS_5 represents the critical soil salinity at some SS = 5 level. This line has been obtained by the prediction method previously described. The straight dashed line represents the cost of quantity ($\bar{Q}$) and quality (C_o) ratio assuming that the cost of a unit amount of water increases with the decrease of its salt concentration. The point O_5 in which the straight line is tangent to the critical iso-soil salinity line is the predicted optimal $\bar{Q}$ - C_o combination. Thus, for any given critical level of soil salinity, and cost ratio, an optimal combination can similarly be derived.

REFERENCES

Bresler, E. 1967. A model for tracing salt distribution in the soil profile and estimating the efficient combination of water quality and quantity under varying field conditions. Soil Sci. 104: 227-233.

Bresler, E. 1973a. Anion exclusion and coupling effects in nonsteady transport through unsaturated soils: I. Theory. Soil Sci. Soc. Am. Proc. 37: 663-669.

Bresler, E. 1973b. Simultaneous transport of solute and water under transient unsaturated flow conditions. Water Resour. Res. 9: 975-986.

Bresler, E. 1975. Two-dimensional transport of solutes during nonsteady infiltration from a trickle source. Soil Sci. Soc. Am. Proc. 39: 604-613.

Bresler, E. and R. J. Hanks. 1969. Numerical method for estimating simultaneous flow of water and salt in unsaturated soils. Soil Sci. Soc. Am. Proc. 33: 827-832.

Bresler, E. 1972. Control of soil salinity. *In* D. Hillel, ed., Optimizing the soil physical environment toward greater crop yields. Academic Press, Inc., New York.

Edwards, D. G., A. M. Posner, and J. P. Quirk. 1965. Repulsion of chloride ions by negatively charged clay particles. Part 3 Di- and trivalent cation clays. Trans. Faraday Society 61:2820-2823.

Hanks, R. J., A. Klute, and E. Bresler. 1969. A numerical method for estimating infiltration, redistribution, drainage and evaporation of water from soil. Water Resour. Res. 5:1064-1069.

Magdoff, F. and E. Bresler. 1973. Evaluation of methods for reclaiming sodic soils with $CaCl_2$. *In* A. Hadas et al., eds., Physical aspects of soil water and salts in ecosystems. Ecological Studies No. 4. Springer-Verlag, Berlin. p. 441-452.

Neuman, S. P., R. A. Feddes, and E. Bresler. 1975. Finite element analysis of two-dimensional flow in soils considering water uptake by roots: I. Theory. Soil Sci. Soc. Am. Proc. 39: 224-230.

Oster, J. D. and J. D. Rhoades. 1974. Calculated drainage water compositions and salt burdens resulting from irrigation with western U. S. river waters. J. Environ. Qual. 4: 73-78.

Warrick, A. W., J. W. Biggar, and D. R. Nielsen. 1971. Simultaneous solute and water transfer for an unsaturated soil. Water Resour. Res. 7: 1216-1225.

Yaron, D., H. Bielorai, J. Shalhevet, and Y. Gavish. 1972. Estimation procedures of response functions of crops to soil water content and salinity. Water Resour. Res. 8: 291-300.

SALINITY EFFECTS ON CORN YIELD, EVAPOTRANSPIRATION, LEACHING FRACTION, AND IRRIGATION EFFICIENCY

J. Ian Stewart, Robert M. Hagan and William O. Pruitt [1]

INTRODUCTION

Research Background

The period of growth and production facing a newly planted seed poses one overriding question. The question is how successful the conspiring factors of an imperfect environment will be in reducing actual yield below the genetic potential? This question lies at the conceptual center of the approach being taken by the writers to quantitative prediction of the impacts of salinity in irrigation waters, both on crop yields and on the resultant levels of salinity in the soil and in **return water flows.**

A major environmental factor in crop production, often the limiting factor, is water. A long term study of "water production functions" and associated management equations for major irrigated crops was initiated at Davis, California in 1969. Findings with corn and grain sorghum to 1973 have been published (Stewart et al., 1973, 1974, 1975a). The essence of these findings is that where water is the principal limiting factor the minimal rate of decline in grain yield (of either crop) is proportional to the seasonal ET deficit, i.e., to the difference between maximum ET (ET_M) and actual ET (ET_A). The relative value slopes of these linear yield versus ET functions differ greatly between crop types, and somewhat between varieties of the same crop, but remain constant for given varieties.

The words "minimal rate of decline" above apply when water quantity alone limits yield. Further yield losses may occur when the problem of timing of ET deficits with respect to crop growth stages is also a factor. This is particularly true in the case of corn when water is in deficit supply during the pollination period and there has been no earlier water shortage. However, even this well known effect is greatly lessened if the crop has experienced prior vegetative period water deficits, i.e., if the plants have been "conditioned" (Stewart et al., 1975a).

Joint Research by Universities of the Consortium for International Development

In 1974 the Office of Water Research and Technology (OWRT) assumed principal sponsorship of these studies, which were at that time broadened to include the salinity variable, and made into a joint research effort by four member universities of the Consortium for International Development (CID).

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In addition to UC Davis, these are Utah State University, Colorado State University, and the University of Arizona.

During the 1974 and 1975 seasons identical field experiments with corn were carried out at Davis; Logan, Utah; Ft. Collins; Colorado, and Yuma, Arizona. Principal experimental variables were applied water (both seasonal depths and timing), soil salinity, and salinity of the irrigation water. These were measured in the experiments, as were resultant crop growth and yields. Additional measurements were made of all factors required to calculate the sequences of actual ET in each treatment as related to the ET requirements (ET_M) in each growth stage.

With respect to ET requirements, an important adjunct to the Davis investigations was the large floating lysimeter located on the experimental grounds (Goddard, 1970). It was employed as an integral part of the experiments to be described, and provided accurate daily measurements of ET_M.

The experimental design adopted for the CID coordinated experiments was the "Line Source" design developed in Utah (Hanks et al., 1974). Detailed treatments and research techniques were developed by the four research teams in consultation.

This report is limited to some specific findings at Davis which are peripheral to the intended scope of the joint research report, presently in preparation. Whether or not support for the findings presented will be forthcoming from the other CID research sites can only be determined after completion of analyses presently underway.

Some common aspects of the CID experiments will be described, then followed by details peculiar to the Davis treatments of interest in this paper.

A principle followed in planning and establishing the CID experiments was to assure that water and/or salinity were in fact the main yield limiting factors. Thus at each site a locally adapted corn hybrid was planted, and all inputs and practices were made as nearly optimal as present knowledge would permit. This includes plant population and spacing, fertilization, tillage, weed control, pest and disease control, etc.

Careful measurements were made of weather and soil characteristics affecting the crop water regime. Foremost among weather factors of interest were rainfall and evaporative conditions, the latter being measured by Class A Evaporation Pan. Chief soil concerns were depth, water holding capacity, and structural inhibitions to water and root movement. All experimental plot areas were preirrigated to assure that the soil profile (to a depth of 10 feet [3 meters] wherever possible) was brought to its well drained water holding capacity by the time of planting.

Following germination, the sole source of irrigation water for any given experimental plot was a single line of close spaced (6.1m apart) sprinklers running parallel to the corn rows through the center of the plot. Sprinkler heads were of a type selected to distribute a triangular water pattern. Maximum application depth was at the sprinkler line, diminishing evenly and reaching the zero application level approximately 15m on either side of the lateral.

Applied water depths were measured by rain gauges spaced across the plots in lines perpendicular to the sprinkler laterals. Soil water content for depletion calculations was measured at the same sites, using neutron probes to take weekly readings at 30cm depth intervals to 3m.

Grain yields and total dry matter production were measured in individual rows, each of which enjoyed a different water regime.

For studies of growth stage effects the season was divided into three major growth periods. These were the Vegetative Period (to 1st tassel), the Pollination Period (to blister kernel), and the Maturation Period, ending at physiological maturity. The control treatment (III) was based on a regular schedule of multiple irrigations extending into all 3 major growth periods, with a fixed depth of water applied in each irrigation. The overall depth of applied water was planned to be excessive near the sprinkler lateral, adequate in nearby rows, then increasingly deficient until no irrigation at all was applied. The check treatment was located on normal soil (S_o), and irrigated with normal irrigation water for the research site in question WO_o). Thus full designation of the control treatment was III-S_o-WQ_o.

Irrigation timing treatments designed to evaluate effects of acute ET deficits in the Vegetative and Pollination Periods were an important aspect of the greater study, but will not be discussed further here.

Saline soil was created at each research site by preirrigating with a large amount of highly salinized water. The objective was to affect the entire soil profile to a 3m depth, and to increase the EC_e of the saturation extract to approximately 5 mmho/cm, hence the designation S_5 for this soil.

Saline irrigation water (WQ_2) was also created at each site. The common objective was to simulate the total salinity (1350ppm or EC = 2) and types of salts predicted (if certain circumstances prevail) in the Colorado River in the year 2000. This was accomplished in each instance by mixing the appropriate salts in a portable swimming pool with the amount of water needed to irrigate one plot, just prior to the application.

Salinity Experiments at Davis

The findings reported here are from the 1974 and 1975 experiments at Davis in which irrigation scheduling was constant, but soil and water salinity levels were varied. Each plot of interest here received 9 weekly irrigations averaging close to 50mm each near the sprinkler lateral. Irrigation began 4 weeks after planting, or about 3 weeks after emergence, and continued until the Maturation Period began at the blister kernel stage. Therefore, water quantity was varied with distance from the line source, but water deficits at all levels of magnitude were distributed evenly in time

Table 1 - Salinity of normal (S_o) and salinized (S_5) soil profiles of increasing depths, in June before irrigation treatment began, and in October, both at unirrigated sites, and where seasonal irrigation depths averaged 154 mm. Davis, California, 1975.

Depth of Soil Profile (cm)	- Soil Salinity - Electrical conductivity of the saturation extract (EC_e,mmho/cm) Mean values to the specified soil depths					
	S_o			S_5		
	June	October		June	October	
	Before Irr	No Irr	154 mm Irr	Before Irr	No Irr	154 mm Irr
15	1.2	2.9	2.4	5.2	10.4	6.5
45	.9	1.7	1.7	3.7	5.6	4.9
75	.9	1.1	1.2	3.3	4.6	4.3
105	[.9]	[.9]	[1.0]	[3.2]	[4.1]	[4.3]
135	.9	.9	.9	3.1	3.9	3.7
165	1.0	.8	.8	3.0	3.6	3.5
195	1.0	.8	.8	2.9	3.3	3.3
225	.9	.8	.8	2.8	3.2	3.2
255	.9	.7	.7	2.7	3.1	3.0
285	.9	.7	.7	2.6	2.9	2.9

throughout the growing season, eliminating growth stage effects as a factor.

At Davis the control treatment (III-S_o-WQ_o) was on soil with an EC_e of the saturation extract of approximately 1.0, and was irrigated with well water of 1.2 mmho/cm (800ppm total salts). In the saline water treatment (III-S_o-WQ_2), salinity of the irrigation water was increased as noted to 1350ppm, or an EC_w of 2.0. For the saline soil and water treatment (III-S_5-WQ_2), half of the land area of the III-WQ_2 plot was preirrigated with 70cm of water of 10000ppm total salt content. The results may be seen in Table 1 which gives EC_e values for soil profiles of increasing depths in both the S_o and S_5 areas, at the beginning and at the end of the irrigation season. The figures in the table are averages for all plot areas treated, to illustrate the general salinity levels dealt with and the ways in which they changed in response to cropping with and without irrigation. Specific levels found in the individual plots of interest will be given later in Table 4 in connection with prediction.

Across the central portion of each plot where the water application pattern was most uniform, two strips were designated for measurements of water and production. Water measurement sites were established in every 4th plant row through the centers of the measurement strips. At each of the sites a neutron probe access tube was sunk to a depth of 3m, and a rain gauge was installed on a pipe within the access tube. This arrangement permitted measurement of applied water and soil water depletion at the same locations, and the pipe was adjustable so the rain gauge could be set at the top of the leaf canopy at the time of irrigation.

Altogether there were 12 water measurement sites in each harvest strip, with 6 on each side of the sprinkler lateral, each receiving a different level of applied water. In the 2 harvest strips this made a total of 24 water measurement sites per plot, or 6 levels of water application repeated 4 times. Salination of half of the III-WQ_2 plot in 1975 reduced the number of water measurement sites to 2 at each water application level in the III-S_o-WQ_2 and III-S_5-WQ_2 treatments. Grain yield at each water measurement site was taken as the average determined in the instrumented row and the 2 flanking rows. Row lengths harvested for yield were 6.1m in 1974, and 12.2m in 1975.

Presentation of Findings and Discussion

Table 2 summarizes the findings for 1975. For each treatment there are 6 rows of figures representing the 6 water application levels. Columns 2, 3, and 4 respectively show seasonal irrigation depths applied, losses to deep percolation, and depths of irrigation water actually stored in the root zone. In considering these data it is helpful to recall there were 9 irrigations, each a week apart. Thus, for example, water application level 4 of treatment III-S_o-WQ_2 received a total of 182mm of irrigation, equal to an average of approximately 20mm/week. By way of comparison, the seasonal ET requirement was 616mm, of which 421mm were required in the same 9 week period. This averages about 47mm/week.

Columns 5 and 6 of Table 2 show ET_A at each water application level, and the incremental ET which resulted from irrigation. Here we see an in-

Table 2 - Effects of seasonal irrigation depth, and salinity of water and soil on ET, irrigation efficiency, and corn grain yield. Davis, California, 1975.

(1) Treatment and Water Application Level	(2) Seasonal Irr Depth (mm)	(3) Perco-lation Loss (mm)	(4) Stored Irr (mm)	(5) Actual ET (mm)	(6) ET Due to Irr (mm)	(7) Irr Storage Eff (4)/(2)	(8) Eff of Utiliza-tion (6)/(4)	(9) Irr Eff (7)X(8)	(10) Corn Grain Yield (tons/ha @ 15.5% H_2O)
III-S_0-WQ_0 (Averages from 4 measurement sites)									
1	3	0	3	410	3	1.00	1.00	1.00	8.2
2	35	0	35	450	43	1.00	1.23	1.23	9.1
3	87	0	87	498	91	1.00	1.05	1.05	9.9
4	168	0	168	515	108	1.00	.64	.64	10.7
5	318	36	282	599	192	.89	[.68]	.60	11.7
6	406	41	365	612	205	.90	.56	.50	12.0
III-S_0-WQ_2 (Averages from 2 measurement sites)									
1	0	0	0	438	0	NA	NA	NA	7.6
2	25	0	25	472	34	1.00	1.36	1.36	8.6
3	97	0	97	499	61	1.00	.63	.63	9.4
4	182	0	182	553	115	1.00	[.63]	.63	10.7
5	337	50	287	606	168	.85	.59	.50	11.4
6(1-site)	437	89	348	616	178	.80	.51	.41	11.2
III-S_5-WQ_2 (Averages from 2 measurement sites)									
1	0	0	0	324	0	NA	NA	NA	6.0
2	40	0	40	372	48	1.00	1.20	1.20	6.6
3	115	0	115	428	104	1.00	.90	.90	7.6
4	193	0	193	496	172	1.00	[.89]	.89	8.3
5	304	21	283	556	232	.93	.82	.76	8.7
6	430	80	350	564	240	.81	.69	.56	9.9

teresting point. At seasonal irrigation levels up to 87mm or approximately 10mm per application, the incremental ET which resulted exceeded the depth of irrigation.

In the field this phenomenon registered as an increase in soil water depletion, over and above the depletion determined with no irrigation at all. Two points explain how this occurred. First there is the fact that a water application depth of 10mm/week or less only affects the upper layer of soil where, if not completely transpired, the water will all evaporate, even if high in salts. Secondly, this addition to ET appeared to strengthen the crop root system such that a somewhat greater portion of the water in storage at planting time was extracted, than was the case where little or no water was applied (water application level 1).

With respect to water extraction without irrigation, it was sizable, averaging more than 400mm or .69 of ET_M in the normal soil area. However, where the soil was salinized, unirrigated water extraction was only 324mm or .53 ET_M. This effect was faithfully reproduced in other S_5 treatments not shown.

A leading concept underpinning the reported research holds that rainfed and irrigated agriculture represent extremes of the same continuum of crop response to water. Therefore, an understanding of irrigation requirements and of the impacts of irrigation on yield, must be based on an understanding of the expected crop water regime without irrigation. Another way of saying this is that we consider all irrigation to be "supplemental irrigation," with the function of closing all or some planned portion of the gap between crop water requirements (ET_M), and ET_A expected without irrigation.

The figures above which contrast unirrigated ET_A found for the S_o and S_5 soil conditions show clearly that the irrigation requirement of the S_5 soil is greater. This supports a host of earlier findings which indicate crop water uptake is less when the osmotic suction of the soil solution is increased. Later we will deal more completely with the implications this has for irrigation efficiency, leaching requirements, and crop yields.

Columns 7, 8, and 9 of Table 2 show the actual irrigation efficiencies which occurred at each water application level in the 3 salinity treatments. The definition of irrigation efficiency most applicable to our developing predictive methodology for water production functions is "the fraction of applied irrigation water utilized in ET." However, some modification is in order to accommodate the efficiencies greater than 1.0 seen at low water application levels in columns 8 and 9. So we will define it here as incremental ET_A resulting from application of irrigation water, expressed as a fraction of the irrigation depth.

Column 9 (irrigation efficiency) is the product of the storage and utilization efficiencies seen in columns 7 and 8. Column 7 shows the fractions of applied water actually stored in the root zone, i.e., applied water less deep percolation, expressed as a fraction of applied water. Column 8 expresses ET_A as a fraction of the stored irrigation water, and it is this fraction which may exceed 1.0 at low water application levels. Notice however that in no case is this effect large in real terms, amounting at most to 9mm of ET_A (columns 6-4) at water application level 2 of treatment III-S_o-WQ_2.

Column 10 is self explanatory, but it is of special interest to note how the yields attained on the salinized soil were markedly reduced below those from the normal soil at all levels of applied water. This brings us to one of the more basic findings of the entire study, shown in Figure 1.

Figure 1 shows how the grain yield found at the 6 water application levels in the 3 salinity treatments relate to ET_A. Data plotted in the figure are given in columns 5 and 10 of Table 2. In viewing this relationship the reader is reminded that timing or "critical growth stage" effects were not a factor in these III treatments.

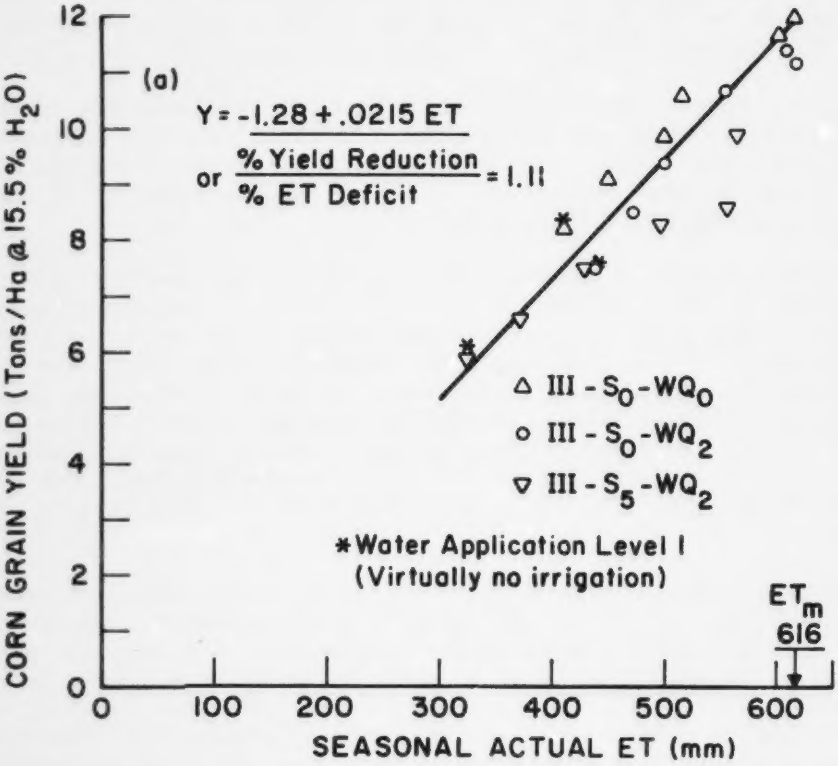

Figure 1 - Functional relation found between corn grain yield and actual seasonal evapotranspiration in three salinity regimes when "critical growth stage" effects were avoided, i.e., when ET deficit sequencing was optimal at all seasonal deficit levels. Davis, California, 1975.

Figure 1 is of interest in several respects. First a very strong linear correlation between yield and seasonal ET_A is evident, and particularly so for the normal soil treatments. This supports earlier findings from field experiments with a different corn variety at Davis, and as earlier noted, with grain sorghum also. The ratio between % Yield Reduction and % ET Deficit shown in Figure 1 is of special interest as discussed below.

The Yield Reduction Ratio (YRR) is a reproducible genetic characteristic of the crop variety defined in a previous paper by the present writers (Stewart et al., 1975a). This ratio quantifies the minimum rate of yield decline relative to (and in response to) ET deficits. In the 1974 and 1975 experiments at Davis, YRRs of the particular variety grown were found to be 1.09 and 1.11. When compared with values of 1.25, 1.34, and 1.20 found for the earlier study variety, they indicate the present variety is superior in drought tolerance.

Most importantly, Figure 1 confirms earlier indications (Stewart et al., 1975b) that the principal effect of salinity is to restrict transpiration, and thereby to reduce yield. This means that a model for predicting yield versus ET relations may incorporate salinity effects directly, along with the effects of other causes of crop water deficits.

The irrigation farmer cannot view his crop water relationships in the context just discussed. He applies water in the amounts he judges best, and hopes for a good crop. Figure 2 more closely illustrates his viewpoint by using the same underlying data (see columns 2 and 10 of Table 2) to relate yields to irrigation amounts.

Symbols used in Figure 2 for the 3 treatments are the same as in Figure 1. Figure 2 shows a clear difference in yields from the normal and salinized soils at all irrigation levels. The noticeable yield upturn at the highest irrigation level on the salinized soil raises the question of what would have happened with still more irrigation. In Figure 1 the same jump in yield appears, accompanied by very little increase in ET. A closer look at Figure 1 shows the lower 5 water levels in the S_5 treatment actually follow a lower slope than that of the fitted regression line, but due to the upturn at level 6, the only strong departure from the line is at water level 5.

The writers believe the reduced slope of the S_5 yield versus ET results at lower water application levels reflects the soil water tension factor, i.e., a relatively greater expenditure of energy by the crop for each unit of ET_A. The upturn at level 6, accompanied by very little increase in ET, appears to result from lessening of the soil water tension. Increased irrigation above level 6 in an attempt to gain more yield from this effect would soon be counterbalanced by reducing soil aeration.

As seen in Figure 2, yield differences resulting from the two irrigation water salinity levels were small in 1975, and cannot be established statistically with these data. Nevertheless, the yield findings in both years favor the use of the lower salinity water. This is reinforced by the information in Table 3 which shows results from 1974.

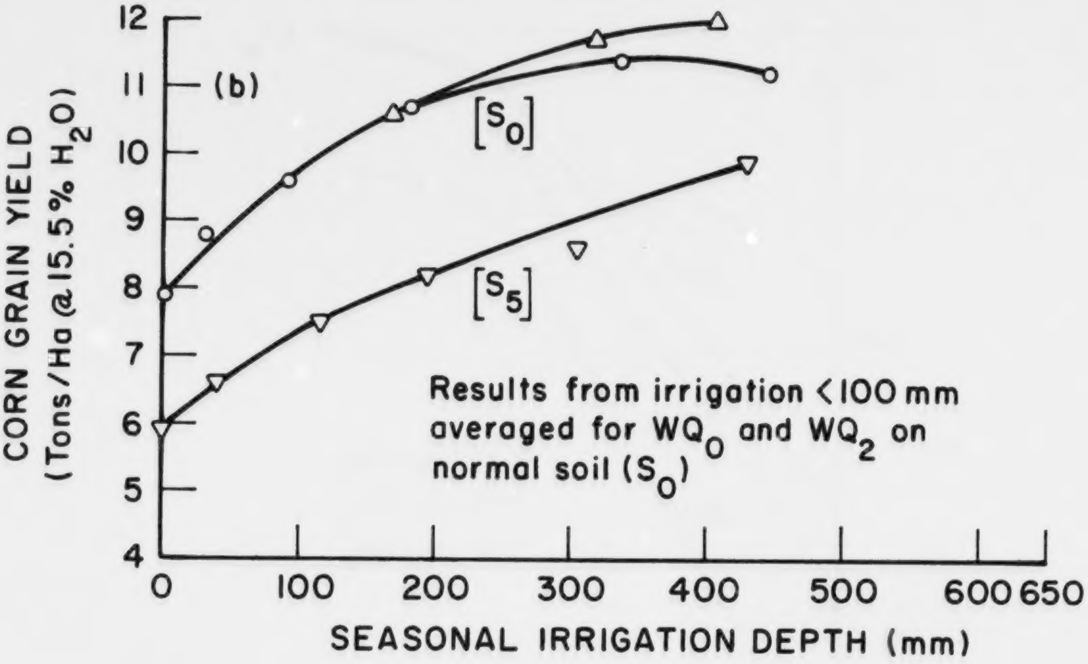

Figure 2 - Corn yield responses to irrigation under 3 salinity regimes at Davis, California, 1975.

Figure 3 shows findings which are central to the theme of this paper. Data points in the figure are taken from columns 4 and 5 of Table 2, and the lines in the figure are drawn by eye in a manner which illustrates the hypothesis being advanced. The essence of the hypothesis is that plants will always refuse, or be unable to transpire, some fraction of irrigation water stored in the root zone, even when the crop is suffering ET deficits from underirrigation. This "Refusal Fraction" (RF) may be of considerable magnitude, and is of vital importance to improved quantitative estimates of actual ET and associated yields, as well as calculations of real irrigation efficiencies, and planning for realistic leaching fractions.

Continuing the suggestion, the RF is unique to the individual cropping circumstances. It depends on crop species and variety, and on the salinity of the irrigation water. The RF in any particular situation increases in direct proportion to the latter, and, as a first approximation, decreases in direct proportion to soil salinity. The latter statement says in effect that an irrigation water of given electrical conductivity (EC_w), will be utilized more efficiently as soil salinity or electrical conductivity of the saturation extract (EC_e) increases. This requires further explanation.

Van Schlifgaarde et al. (1974) extrapolate functional relations between relative values of crop yield and EC_e to the zero yield point, and

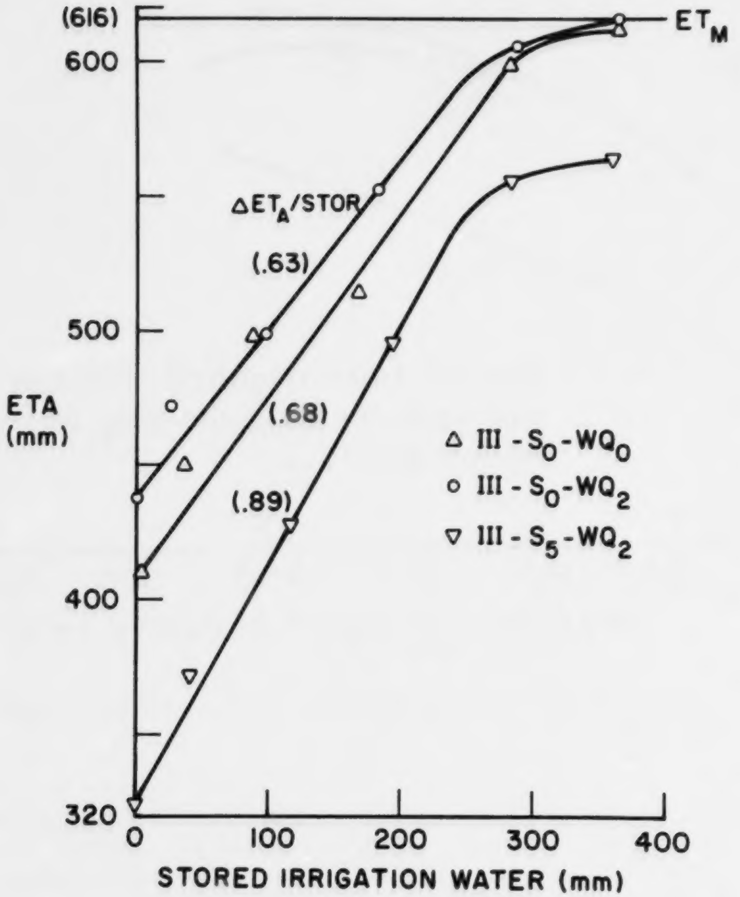

Figure 3 - Rates of increase in ET_A of corn in response to increased irrigation water availability, as influenced by salinity levels of the soil and the applied water. Davis, California, 1975.

propose that the EC_e levels so determined represent the limits to which the crops in question can concentrate soil water. Bernstein and Francois (1973) grew alfalfa in suction lysimeters in the greenhouse at Riverside, California, and found that the maximum EC of the soil water (maximum EC_{SW}) reached about 35mmho/cm. They propose a "minimum permissable leaching fraction" or leaching requirement (LR), which is calculated by dividing the salinity of the irrigation water by the maximum EC_{sw} the particular crop type is able to produce. For example, for alfalfa irrigated with water of electrical conductivity 1.0, LR = EC_w/max EC_{sw} = 1/35, or about 3% of the applied water.

The above authors find that a salt balance can be maintained in the root zone using this minimum leaching fraction, with a yield reduction in alfalfa of about 8% from the level produced with a more conventional leaching fraction 4 times greater. The principal conclusion reached by these workers is that so long as a salt balance is maintained in the root zone, salinity of the irrigation water (above some threshold value for the given crop) is the factor affecting yield most. They further point out that the effect of salinity on crop yield directly reflects diminished water uptake by the crop.

The publications cited above point out that the minimum leaching fraction concept may not be directly applicable in the field due to the stringent management requirements, but that leaching fractions well below those suggested by earlier work may be feasible in terms of continuing to produce high yields. Advantages would be reduced water demands, and reduced salt loads in return flows (gross, not concentration).

The new FAO guidelines (Ayers et al., 1976) for managing waters of different salinity levels give consideration to the minimum leaching fraction concept, but modify field recommendations by assuming an actual leaching fraction of about 15%. This is still well below many recommendations of the past.

Our findings with corn agree completely with the works cited and others that yield reductions due to salinity reflect reduced water uptake (see Figure 1), but suggest the field application of any management program involving near minimum leaching fractions may not be feasible for annual crop production on other than already saline soils.

The question revolves around the attainable maximum value of EC_{sw} with a given annual crop on a given cropping season. The maximum values of EC_{sw} suggested by workers at the U. S. Salinity Laboratory, and recently updated by Maas and Hoffman (1976) represent, as previously noted, what are essentially zero water uptake and production levels. The maximum EC_{sw} suggested for corn (grain) is approximately 20 mmho/cm, equivalent to an EC_e value of about 10 mmho/cm. As Bernstein and Francois (1973) explain, this degree of salt concentration can only be tolerated near the bottom of the root zone, while the crop draws the great bulk of its water from the frequently irrigated upper root zone.

However, our findings indicate that the maximum concentration of salts in soil water that corn can bring about in a given season is conditioned by the salinity of the upper soil profile in which germination and early root activity take place. If we relate this "Limiting Salt Concentration" (LSC, expressed as EC in mmho/cm) only to the applied water which is effectively stored in the root zone (as opposed to the total soil solution per se), our data indicate it equals 6.4 EC_e for the corn variety studied. For example, if EC_e of the upper soil profile at planting is 1.0, irrigation water later stored in the root zone can be concentrated to a maximum of 6.4 mmho/cm when the crop is stressed.

The above suggests that a predictable "Refusal Fraction" (RF) exists for any given irrigation water, which is dependent on the crop type and variety, and on the salinity of the soil and water as follows: $RF = EC_w/6.4\ EC_e$, for our corn variety, and for a soil salinity sample to a depth of 1 m.

Table 3 - Effects of seasonal irrigation depth, and salinity of water and soil on ET, irrigation efficiency, and corn grain yield. Davis, California, 1974.

(1) Treatment and Water Application Level	(2) Seasonal Irr Depth (mm)	(3) Percolation Loss (mm)	(4) Stored Irr (mm)	(5) Actual ET (mm)	(6) ET Due to Irr (mm)	(7) Irr Storage Eff (4)/(2)	(8) Eff of Utilization (6)/(4)	(9) Irr Eff (7)X(8)	(10) Corn Grain Yield (tons/ha @ 15.5% H_2O)
III-S_o-WQ_o(Averages from 4 measurement sites)									
1	5	0	5	435	5	1.00	1.00	1.00	6.9
2	58	0	58	485	55	1.00	.95	.95	8.2
3	153	0	153	555	125	1.00	.82	.82	9.9
4	253	6	247	636	206	.98	[.83]	.81	11.0
5	389	11	378	674	244	.97	.65	.63	11.7
6	500	69	431	674	244	.86	.57	.49	11.6
III-S_o-WQ_2(Averages from 4 measurement sites)									
1	4	0	4	425	4	1.00	1.00	1.00	6.8
2	66	0	66	474	53	1.00	.80	.80	8.3
3	158	1	157	538	117	.99	.75	.74	9.5
4	277	8	269	608	187	.97	.70	.68	10.6
5	415	55	360	673	252	.87	[.70]	.61	11.1
6	504	78	426	674	253	.85	.59	.50	11.4

Note: ET_M determined on the large floating lysimeter in 1974 was 674 mm.

Evidence for the above may be seen in columns 4 and 5 of Tables 2 and 3, and in Figure 3. The figure shows how ET_A of the crop increased with (stored) irrigation under 3 different salinity regimes, and approached ET_M as determined on the lysimeter. In Figure 3 the data suggest dividing stored water depths into three **categories**. Seasonal irrigation depths less than 100 mm were fully evapotranspired, and, as earlier explained, in some instances caused slightly greater exploitation of planting time soil water than occurred in the unirrigated areas. From 100 - 300 mm of stored irrigation water (and somewhat more in 1974 because ET_M was higher at 674 mm), is the range of greatest interest. It represents individual irrigation depths sufficient to penetrate below the evaporation layer, but insufficient to satisfy the water needs of the crop. Therefore, throughout this range the crop was stressed prior to each irrigation, and following cessation of irrigation, **for most of the Maturation Period. It is in this range of irrigation levels we can evaluate the RFs for the 2 waters applied in the 3 salinity treatments.**

At stored irrigation water levels above 300 mm, Figure 3 shows ET_A essentially reaches ET_M, or, as in the case of the salinized soil, levels off at some lower maximum ET value established by delayed early development.

In Tables 2 and 3, column 8 provides the same information seen in Figure 3. In each treatment in both experimental years, column 8 shows either 2 or 3 similar values for effectiveness of stored water utilization in the middle irrigation range. In each instance the last of these figures is bracketed, and is regarded as the key figure for evaluation of RF.

Accordingly, in Figure 3 the lines are drawn straight from the unirrigated ET_A levels to the points bracketed in the tables, after which ET_M is soon approached. The slopes of the straight portions of the curves are shown in parentheses on the figure, as well as being bracketed in the tables. They represent the fraction of stored irrigation water the crop was able to extract when under stress, and are equal to 1-RF in each instance. Corresponding RF values for the 3 salinity regimes in 1975 were .37 (III-S_0-WQ_0), .32 (III-S_0-WQ_2), and .11 (III-S_5-WQ_2). In 1974 RF values were .17 (III-S_0-WQ_0) and .30 (III-S_0-WQ_2).

To utilize such information as the above in the field requires a strict definition of the upper soil profile and a standard sampling approach. This approach must consider the behavior of salinity in the soil, and of the plant during its early growth period when the conditioning to soil salinity level appears to take place. Table 1 shows us some aspects of salinity behavior in the two experimental soil conditions. Each value for EC_e in Table 1 represents the average salinity of the entire soil profile to the depth indicated. A soil sampling depth must be selected which adequately characterizes the salinity conditions the plant will encounter in its early life.

We have selected a depth of 1 m (bracketed figures at the 105 cm depth in Table 1) because a] as the data indicate, most of the rapid fluctuations in soil salinity occur within that depth, b] most agricultural soils are that deep or deeper ,c] it is a practical depth for sampling purposes, and

Table 4 - Predicted LSC* values for corn grown on soils of different salinities, followed by predicted and observed values of RF_{corn}+ for irrigation waters of 1.2 and 2.0 mmho/cm salinities. Davis, California, 1974 and 1975.

Year & Treatment	EC_e, 1m (mmho/cm)	EC_w (mmho/cm)	LSC_{corn} (mmho/cm)	RF_{corn} Predicted	RF_{corn} Observed
1974, III-S_o-WQ_o	0.9	1.2	5.8	.21	.17
III-S_o-WQ_2	0.8	2.0	5.1	.39	.30
1975, III-S_o-WQ_o	0.9	1.2	5.8	.21	.32
III-S_o-WQ_2	0.9	2.0	5.8	.35	.37
III-S_5-WQ_2	2.8	2.0	17.9	.11	.11

* LSC_{corn} or Limiting Salt Concentration is the electrical conductivity to which irrigation water added to the root zone can be concentrated before uptake by the crop ceases. The formula used in calculating it follows:

$$LSC_{corn} = 6.4\ EC_e,\ 1m \qquad [LSC \leq 20]$$

where 6.4 is an empirical factor determined in the 1974, 1975 experiments at Davis.

+ RF_{corn} or Refusal Fraction is the fraction of stored irrigation water not available for transpiration by the crop due to the limitation imposed by the LSC. Calculation of RF is straightforward as follows:

$$RF_{corn} = EC_w/LSC_{corn}$$

d] the early root activity of the crop is in that zone. Our data show water uptake below the depth of 105 cm began 6 weeks after planting, or 5 weeks after emergence at the time of full canopy establishment (Leaf Area Index $= \sim 3$), or 2 weeks before 1st tassel. Exactly when the conditioning of the crop takes effect is a matter of conjecture, but if in fact there is conditioning of the type suggested here, it likely takes place before the roots are active below the 1 m depth.

Adopting the 1 m soil sampling depth, and applying the equations shown for LSC_{corn} and RF_{corn}, Table 4 has been developed. The table incorporates our measured values of EC_w and EC_e, and the empirically derived applied water concentration factor of 6.4 to predict values of LSC_{corn} and RF_{corn} for the different treatments in 1974 and 1975. The predictions are then compared with the observed values.

Conclusions

1] The effect of salinity on crop production is a direct reflection of reduced water uptake and transpiration. Relations found between yield and ET are, as a first approximation, equally as valid for predicting the effects of water deficits due to salinity as for deficits due to limited water supply.

2] Methods for calculating leaching requirements which do not consider present soil salinity levels or crop conditioning factors may not be adequate, particularly for guiding irrigation of annual crops. Short term consequences of such calculations may cause the following misjudgements: (i) overestimation of salt leached from the profile, (ii) overestimation of actual ET, (iii) consequent overestimation of anticipated crop yields and of real irrigation efficiencies. Long term consequences may include inadvertantly salinized soils, and unplanned impairment of productive capacity.

3] The level to which salts brought into the root zone with irrigation water can be concentrated by an annual crop is not necessarily the maximum concentration of which that crop type is capable. Rather, it is a different level in every cropping situation. This paper defines a "Limiting Salt Concentration" or LSC which for a given crop variety is dependent on the salinity of the upper soil profile in which germination and early root activity take place.

4] Together the LSC and the salinity of the applied water determine the "Refusal Fraction" or RF, defined here as the fraction of irrigation water which, if stored in the root zone, cannot be utilized by the crop in transpiration, even if severely water stressed. The RF is an important consideration in calculating actual ET and related yield expectations, real irrigation efficiencies, and leaching fractions capable of maintaining current soil salinity levels.

5] LSC and RF values applicable to specific cropping situations are estimable from routine measurements of soil and water salinities, i.e., EC_e and EC_w.

REFERENCES

Ayers, Robert S., and Dennis W. Westcot. 1976. Water quality for agriculture. FAO-United Nations, Rome. (In press).

Bernstein, Leon, and L. E. Francois. 1973. Leaching requirements studies: sensitivity of alfalfa to salinity of irrigation and drainage waters. Soil Sci. Soc. of America Proceedings 37:931-943.

Goddard, W. B. 1970. A floating drag-plate lysimeter for atmospheric boundary layer research. Journal of Applied Meteorology 9:373-378.

Hanks, R. J., J. Keller, and J. W. Bauder. 1974. Line source sprinkler plot irrigation for continuous variable water and fertilizer studies on small areas. CUSUSWASH 211D-7, Utah State University. 13p.

Maas, E. V., and G. J. Hoffman. 1976. Crop salt tolerance - current assessments. U. S. Salinity Laboratory publication. (In press).

Stewart, J. Ian, and Robert M. Hagan. 1973. Functions to predict effects of crop water deficits. Journal of the Irr. & Dr. Div., ASCE 99-IR4:421-439.

Stewart, J. Ian, Robert M. Hagan, and William O. Pruitt. 1974. Functions to predict optimal irrigation programs. Journal of the Irr. & Dr. Div., ASCE 100-IR2: 179-199.

Stewart, J. Ian, R. D. Misra, W. O. Pruitt, and Robert M. Hagan. 1975a. Irrigating corn and grain sorghum with a deficient water supply. TRANSACTIONS of ASAE 18-2: 270-280.

Stewart, J. Ian, W. O. Pruitt, P. E. Martin, J. D. Prato, and Robert M. Hagan. 1975b. Determination of water production functions and water utilization patterns of principal crops, required for water resources planning and management. Summary report, California contributing project report, Western Regional Research Project W-67. 8p.

van Schilfgaarde, Jan, Leon Bernstein, James D. Rhoades, and Stephen L. Rawlins. 1974. Irrigation management for salt control. Journal of the Irr. & Dr. Div., ASCE 100-IR3: 321-338.

RESISTANCE TO SODA SALINIZATION OF SOME IRAQI SOILS

A. H. Alzubaidi[1]

INTRODUCTION

Sodium carbonate is considered one of the most toxic salts accumulating in arid and semi-arid soils. In addition to its toxic effect on plant growth, it has a very deteriorative effect on soil. Therefore it is important to understand the processes governing the accumulation and disappearance of this salt in different layers of soil profiles. Moreover, such understanding has a considerable value in cases when saline water containing soda is used for irrigation and reclamation purposes.

In evaluation of irrigation water regarding carbonate and bicarbonate hazard, Eaton (1950), introduced the term "Residual Sodium Carbonate" (RSC), which is calculated as follows

$$RSC = (CO_3 + HCO_3) - (Ca + Mg)$$

where all ions are expressed me/1.

Wilcox (1955) concluded that if RSC is more than 2.5 me/1, the water is not suitable for irrigation. Arany (1956), however, has shown that in the evaluation of the effect of RSC the soil type should be taken into account. Van Hoorn (1970) has mentioned that few data are available on this subject.

Due to the presence of soluble and exchangeable divalent cations (calcium and magnesium) and gypsum in most soils of arid regions, much of the sodium carbonate in irrigation and reclamation water disappears as soon as such water comes in contact with surface layers of the soil profile. Sodium carbonate reacts with divalent cations to form a precipitate of calcium and magnesium carbonate. This leads to an increase of soluble sodium percentage and, thus, the sodium hazard will increase.

The capcity or ability of soil to precipitate free carbonate ions is termed "soil resistance to soda salinization" (c-value) and is expressed in me/100 gm of soil (Bobkov, 1969).

On the basis of the c-value, Bobkov has classified dirrerent soils into five groups: high, moderate, weak, very weak, and soils with no resistance to soda accumulation, with c-values more than 50, 35-50, 20-35, 10-20, and 0-10 me per 100 grams of soil, respectively.

Such an evaluation, which considers the soil properties, helps us to predict where saline water containing soda could be used with or without danger of soda salinization. Therefore the purpose of this study was to test the resistance of some Iraqi soils to soda salinization. Such findings have a considerable value in managing saline water for irrigation and reclamation of different types of soils.

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MATERIALS AND METHOD

Nine soil samples collected from different depths of different soil profiles representing different locations of Iraq were used in this study. Chemical and physical properties of these samples were reported in a previous paper (Alzubaidi and Pagel, 1974). All samples were ground and passed through a 2 mm screen. Ten grams of each sample was mixed with 50 ml of sodium carbonate solution (0.1 N) in an Erlenmeyer flask, shaken and left to stand overnight. The mixture was filtered and the filtrate was kept for sodium carbonate determination. Sodium carbonate was determined by titration with sulfuric acid (0.1 N) and soil resistance to soda salinization (c-values) were calculated using the following formula (Bobkov, 1969):

$$C = (A - B)\ 50T,$$

where C is soil resistance to soda salinization in me/100 gm soil; A is double volume of H_2SO_4 used for titration of the blank; B is a double volume of H_2SO_4 used for titration of 10 ml of soil extract, and T is sulfuric acid normality.

To discover the role of soluble salts in soil on soil resistance to soda salinization, four of the samples were selected for further study. One hundred grams of each were transferred to a special glass column and leached with distilled water. Leaching was stopped when the EC of the leachate became less than 4 mmhos/cm. The c-values after leaching were determined for these samples as described above.

RESULTS AND DISCUSSION

The obtained results of this study are summarized in Tables 1 and 2. Table 1 gives the c-values for the original soils and Table 2 gives them for four of the soils after removal of soluble salts. The c-values for different soil depths and different soil profiles indicate that the studied soil samples have weak and moderate resistance to soda salinization. Soil samples with no resistance to soda salinization were not found in this study.

Precipitation of the carbonate of sodium carbonate in different soils could result by one or more of the following reactions (Egrov, 1954; Antipov-Karataev, 1958; Kovda, 1973; Bazilevich, 1965):

1. Reaction of soda with soluble divalent cations of soil solution:

$$Na_2CO_3 + CaCl_2 \dashrightarrow CaCO_3 + 2NaCl \qquad (1)$$
$$Na_2CO_3 + MgCl_2 \dashrightarrow MgCO_3 + 2NaCl \qquad (2)$$
$$Na_2CO_3 + MgSO_4 \dashrightarrow MgCO_3 + Na_2SO_4 \qquad (3)$$

Table 1: Soil resistance to soda salinization (c-values) for studied soil samples

Profile No.	Location	Depth, cm	C-value, me/gm Soil	Soil Resistance to Soda Formation
5	Tell-Affar	0-14	29.00	weak
		14-22	24.00	weak
		22-34	25.00	weak
59	Sulamania	0-25	42.50	moderate
		25-55	44.00	moderate
		55-100	43.80	moderate
		100-120	36.00	moderate
		120-140	26.50	weak
2	Abu-Ghraib College of Agriculture	0-30	49.25	moderate
		30-60	40.00	moderate
		60-100	33.50	weak
		100-150	33.00	weak
26B	Abu-Ghraib	0-5	32.50	weak
		5-20	30.00	weak
		20-40	28.00	weak
		40-70	29.00	weak
		70-120	40.00	moderate
21	Al-Yosifia	0-30	49.00	moderate
		30-40	27.00	weak
		40-70	21.90	weak
		70-120	28.50	weak
19	Sur-Kisra	0-30	31.30	weak
		30-60	28.80	weak
		60-90	27.80	weak
		90-120	29.00	weak
10	Al-Dalmag	0-12	49.00	moderate
		12-53	27.20	weak
		53-90	28.00	weak
		90-140	34.00	weak
44	Al-Diwania	0-20	31.50	weak
		20-50	38.00	moderate
		50-80	40.00	weak
		80-150	34.00	weak
34	Shatt-Al Arab	0-2	50.00	high
		2-15	49.00	moderate
		15-30	25.00	weak
		30-80	18.00	very weak

Table 2: Soil resistance to soda salinization (c-values) before and after removal of soluble salts

Profile No.	Depth, cm	C-value, me/100 gm Soil Before Removal of Soluble Salts	C-value, me/100 gm Soil After Removal of Soluble Salts
2	0-30	49.25	48.00
	30-60	40.00	29.50
	60-100	33.50	27.50
	100-150	33.00	30.00
10	0-12	49.00	30.00
	12-53	27.00	28.50
	53-90	28.00	28.00
	90-140	34.00	29.00
44	0-20	31.50	29.00
	20-50	38.00	33.00
	50-80	40.00	40.00
	80-150	34.00	31.00
34	0-2	50.00	50.00
	2-15	49.00	40.00
	15-30	25.00	18.00
	30-80	18.00	15.00

2. Reaction of soda with exchangeable divalent cations through ion exchange reactions:

$$XCa + Na_2CO_3 \longrightarrow CaCO_3 + 2NaX \quad (4)$$
$$XMg + Na_2CO_3 \longrightarrow MgCO_3 + 2NaX \quad (5)$$

3. Reaction of soda with gypsum:

$$Na_2CO_3 + CaSO_4 \longrightarrow CaCO_3 + Na_2SO_4 \quad (6)$$

One or more of these reactions, as mentioned above, could be responsible for carbonate precipitation in our studied samples. Statistical tests show a highly significant positive correlation between c-values and soluble calcium + magnesium ($r = 0.90$). A nonsignificant positive correltion ($r = 0.25$) was obtained between c-values and gypsum content of the soil samples.

These findings indicate that soluble and exchangeable divalent cations (calcium and magnesium) are responsible for carbonate precipitation (reactions 1 to 5). Gypsum may also take place in carbonate precipitation in some soil samples according to equation 6, when its content is relatively high. A nonsignificant correlation between c-values and gypsum content could be attributed to the fact that a large number of the investigated soil samples contained no gypsum.

Removal of soluble salts from the soil samples (profiles 2, 10, 44, and 34) caused a decrease in soil resistance to soda salinization in those samples, as well as in the c-values for the whole profile (Table 2). The differences between the c-values before and after removal of soluble salts are not high, except in some layers (depth 0-12 cm of profile 10 and depth 2-15 cm of profile 34) where the initial content of soluble salts is very high. The slight decrease in c-values in most of the soil samples indicates an important fact: that after the removal of soluble salts from soil samples, exchangeable calcium and magnesium provide soluble calcium and magnesium for carbonate precipitation. This leads to saturation of the soil exchange complex with sodium; in other words, formation of alkali soils. Therefore a special precaution should be made when saline or river water containing sodium carbonate is used for reclaimed soils or during reclamation of saline soils.

RESULTS

The obtained results allow us to suggest the following conclusions:

1. In the evaluation of saline water (drainage, ground, and well water) and river water containing sodium carbonate, it is not sufficient to determine just the RSC value using the Eaton formula; the soil resistance to soda salinization depends on soil properties, should also be tested.

2. Due to the presence of a high quantity of soluble and exchangeable calcium and magnesium in most of the saline soils of Iraq, CO_3-containing water could be used (to some limit depending on the c-value of these soils) for irrigation and during the first stages of reclamation.

REFERENCES

Alzubaidi, A. and H. Pagel. 1974. Chemical Characteristics of Some Iraqi Soils. Beitrage trop. Landwirtschaft u. Veterinarmed. 12, H.3.

Antipov-Karataev, I. N. 1958. Amelioration of Alkali Soils, Academy of Sciences, Moscow.

Arany, S. 1956. Cited from Kovda, V. A., International Source Book on Irrigation, Drainage, and Salinity. FAO/UNESCO publications (1973).

Bazilevich, N. 1965. Soil Geochemistry of Soda Salinization, Moscow.

Bobkov, V. 1969. The Resistance of Soil to Soda Salinization. Pochvovedenie, No. 8.

Eaton, V. 1950. Significance of Carbonate in Irrigation Water. Soil Science 69:123-133.

Egorov, V. 1954. Saline Soils and Their Development. Academy of Sciences, Moscow.

Kovda, V. A. 1973. International Source Book on Irrigation, Drainage and Salinity. FAO/UNESCO publications (1973).

Van Hoorn, I. W. 1970. Quality of Irrigation Water, Limits of Use and Prediction of Long Term Effect. FAO Irrigation and Drainage Paper 7 (Salinity Seminar Baghdad).

Wilcox, L. V. 1955. Determination of the Quality of Irrigation Water. Agriculture Information Bulletin No. 197, USDA.

IRRIGATION WITH SALINE WATER IN THE PECOS VALLEY OF WEST TEXAS

Jaroy Moore and J. J. Hefner 1/

INTRODUCTION

The Pecos Valley of West Texas contains over 200,000 acres (80,000 has) of cropland which requires irrigation throughout the full cropping season. Annual rainfall is less than 12 inches (300mm) and much of this amount occurs in showers of less than one inch (25mm). While much is said about irrigation from the Pecos River, actually less than 8,000 acres (3,200 has) are currently irrigated from this source in the Pecos area. The majority of water must be pumped from underground aquifers with lifts of 200-600 feet (60-180m). Most of the area has been in production for 30 years. Cotton has been the major crop but more interest has developed in small grains, grain sorghum, and alfalfa in the last few years. Limited acreage is devoted to production of cantalope, onions, and bell peppers. Furrow irrigation in rows of one-quarter (0.4 km) to one-half mile (0.8 km) in length is used. This has led to percolation losses on the upper ends of fields and tail-water losses from the lower ends. Irrigation scheduling is based on fixed times of 14 to 21 days between applications.

The primary source of energy for pumping has been natural gas. In January of 1976, a five-fold increase in the price of gas occurred. This increased energy cost, combined with general increases in production cost, has created serious economic problems for the producers of this area. Cotton production in Reeves County has declined from 70,000 acres (28,000 has) in 1964 to 4,500 acres (1,800 has) in 1976. Although some acreage has been replaced by other crops, much of the land is idle at present.

WATER QUALITY

The major problem with waters of this area is the high amount of total salts. Although salinity content varies from well to well, the range in electrical conductivity (EC) is from 1.8 to as high as 9.4 millimhos/cm. Some chemical analyses are given in Table 1 for a "typical" well in Pecos area. Water quality, as defined according to total salt content and sodium adsorption ratio (SAR), is in the C-4, S-2 class according to U. S. Salinity Laboratory Staff (1954). Fortunately, considerable quantities of calcium and magnesium are contained with the sodium. Except for a few shallow wells, most all well waters have SAR values ranging from six to nine. Further analyses are given in an earlier publication by Longenecker and Lyerly (1959).

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Table 1: Chemical Analyses of Water from a Typical Well in the Pecos Area

Total Salts	Cations:me/l		Anions:me/l	
3.5 tons/acre ft.	Calcium	11.6	Carbonate	0.0
2558 ppm	Magnesium	9.3	Bicarbonate	4.1
1496 grains/gal.	Potassium	0.4	Sulfate	9.2
4127 EC X 10^6	Sodium	19.4	Chloride	27.0
pH 7.8	Total	40.7	Total	38.3
Sodium Adsorption Ratio (SAR) 6.0				

In 1976, a sampling program was initiated to monitor the salinity status of selected wells in this area. Decreased pumping and non-use of wells has caused some concern about various aquifers being mixed. Should large amounts of shallow water drain into the deeper aquifers, the salt content of wells currently in use could increase. A few instances of one to two millimhos/cm increases in EC have been noted, but this could be problems in individual wells rather than a general problem.

SOILS

Soils of this area are thought to be formed from limestone and igneous outwash materials from hills and mountains.

Major soils of the Pecos area are the Hodgins, Reakor, Hoban and Reeves series. They are similar in mineralogical properties, with chief differences being in profile characteristics (either lack of or depth to the calcic or gypsic horizon). Soil texture ranges from silt loams to silty clay loams. Clay fractions are composed mainly of illite and mica materials. Profile development is very limited.

The soils are calcareous (pH of 7.5-8.0), with a calcium carbonate equivalent between 20 and 30 percent for many soils, low in organic matter, and show little structural development. Nitrogen is the primary fertilizer element lacking. Phosphorous responses are not usually found with field crops other than alfalfa. Iron deficiencies are beginning to be noted on sorghum crops and may become serious enough to justify treatment.

Infiltration rates are variable, averaging 0.2 inches (0.5 cm)/hour on most soils. Internal drainage is good, with drainage problems being limited to isolated areas. Temporary water tables have been noted below ten feet (3 m) on some areas during the latter part of the irrigation season, but overall the problems associated with drainage are few, thus allowing continued production from these soils without disasterous buildup of salts.

With total salt content of the water near an EC of four millimhos/cm, soils almost without exception are classified as saline soils (U.S. Salinity Laboratory Staff, 1954). Exchangeable sodium percentage the value of 15, according to some analyses (Longenecker and Lyerly, 1959), and therefore approach the classification of saline and alkali soils. Immediately following rainfall, dispersed soil conditions develop, which is typical of the non-saline alkali soils. Resulting crust formations in seed beds are sometimes severe enough to require replanting of crops.

Under furrow irrigation, the EC of the soils in the water furrow are very near that of the irrigation water, while the beds may contain up to six times as much salts as the irrigation water. Generally, the salt content of saturated paste will not be more than two or three times the value of water applied, and in some cases approach the value of the water.

CURRENT MANAGEMENT PRACTICES

Due to the saline soil conditions, several practices are used with furrow irrigation to obtain a favorable salinity status. Some producers plant in the water furrow,which contains the least salts. On crops such as cotton, this has the disadvantage of cooler soil temperature and causes harvest difficulties with the bottom crop. However, where wells are extremely high in salts, this is the most reliable method.

Variable row spacing (Longenecker et al., 1970) is another method used to avoid the high salt content in cotton beds. Pre-plant irrigation is applied in every furrow and then seed beds are located on the shoulder of beds near the water furrow. Alternate furrow water application is followed throughout the remainder of the season. Spacings are 26 inches (66 cm) between plants across the water furrow and 54 inches (137 cm) between plants across the dry furrow, a similar 32-48 inch (81-122 cm) spacing is also used. Both give 80 inch (203 cm) centers for tractor travel. Plantings near the shoulders of the beds are lower in salts than the center. This, combined with the alternate furrow irrigation, allows accumulation of salt beyond the plant row. Additionally this spacing offers a skip row effect with fewer weed control problems.

Similar advantages were found with a multiple row planting method (Hefner, Moore, and Longenecker, 1971). Four rows of cotton are grown on an 80 inch (203 cm) cantaloupe bed. Pre-plant irrigations are on regular 40 inch (102 cm) rows and alternate furrow irrigation is utilized following emergence of the plants. The first row of plants is located 16 inches (41 cm) from center of water furrow and then a 12-24-12 inch (30-60-30 cm) spacing is used across the bed. Emergence has been good, and yields are above single row plantings.

Sprinkler irrigation of alfalfa with moveable solid set systems has been in use for several years. Yields have been equal to or greater than border irrigated fields. Although research data are not available, it appears less water may be used with the sprinkler systems while maintaining a favorable salt balance in the soil profile. Most waters used for sprinkling alfalfa have an EC between 2-4 millimhos/cm, and the only leaf burn observed is in drift areas when climate conditions are conducive to high evaporation rates. In one case, early season leaf burn was noted where waters had an EC of 6.0 millimhos/cm, but economic production appears possible over the season.

FUTURE RESEARCH AREAS

In past years many producers had little interest in water conservation because it did not appear economically justified. Water applications in excess of four acre-feet (12,000 m^3/ha) were not uncommon for a cotton crop (Longenecker, Thaxton,and Lyerly, 1963). Perhaps rates much greater than this figure have been applied, since very few wells have flow meters attached. Regardless, these days are past, and water use efficiency is of prime importance for the area. The most obvious solution is to cut back on the amount of water applied by the present management system. Changes in water management mean that changes in salinity management will also be occurring. Therefore, the total system must sooner or later be considered.

A model such as represented by Jensen (1973) for the soil water balance accounts for several important aspects. It is given as:

$$W_i = Wet + W_L + W_{misc} - R_e - \Delta W_s \quad (1)$$

Where W_i = **Irrigation Water**, R_e = effective rainfall, Wet = **Water** loss by evapotranspiration, ΔW_s = **Change** in soil water, W_L = **Water** for leaching, W_{misc} = **Water** loss by system.

Meteorological data is being collected for development of the Wet term of equation (1). Additionally, this information should eventually indicate whether conditions are sufficiently constant to continue irrigation scheduling based on time, or that variations are such that daily conditions must be taken into account.

Systems of water application, such as sprinkler or furrow systems, are represented by the W_{misc} term. Different amounts of water will be required for different systems of application. Similarly, if equation (1) is considered on an energy basis, more energy will be required where the system must be pressurized.

Water required for leaching purposes must be considered because of the high salt content of the irrigation water. Leaching accomplished with various application systems may be quite different, and benefits of the system need to be evaluated.

Presently, a system that involves a moveable solid set sprinkler and furrow watering devices is being examined. The merits of sprinkler application in establishment of crops are recognized (Mackenzie, 1972). To avoid leaf burn of sensitive crops, furrow irrigation is used following emergence. This is accomplished with furrow emitters on lines in place of sprinkler drag lines. Length of the furrow run can be selected on multiples of 50 feet (15 m). Preliminary results indicate that runs of 150 feet (45 m) with an output of six gallons(23 l)/min per emitter are suitable for this area. Once this system is developed, it can then be evaluated and compared with the conventional systems according to the soil-water balance.

Although the present economic situation does not look especially favorable, the area has the potential for production. Water supplies, though saline, are in sufficient quantity to furnish long term needs. Climatic conditions favor the production of high quality seed crops with sufficient season for most crops (226 days). The primary restraint as to the type crop that can be produced is related to salinity tolerance. Economic conditions may be altered as the population continues to rise and demand becomes more critical for food and fiber. Better definitions of management and systems for production in this area offer assistance locally as well as increasing knowledge about management of saline soils.

SUMMARY

The Pecos Valley of West Texas has been under cultivation for 30 years with pump irrigated saline water averaging 2500 ppm total salts. This quantity of salts has restricted selection of crops to more salt tolerant plant species and required excessive water for leaching. Primary problems are associated with establishment of crops. Once beyond the seedling stage, growth and yield have generally been acceptable. Internal drainage has remained good and severe salt buildup has not occurred because of favorable types of clay minerals and ionic composition of irrigation waters. The major problem facing the area is high production cost, especially that of pumping irrigation water. Expiration of a long term natural gas contract in 1975 led to a 500 percent increase in 1976. This has curtailed farming operations and has placed added emphasis on more efficient use of water. New concepts and modifications of present irrigation management systems are being introduced. The saline nature of the water and soils require that any changes in the overall management systems be carefully investigated to assess its future consequences on agriculture in the area.

LITERATURE CITED

Hefner, J. J., J. Moore, and D. E. Longenecker. 1971. Multiple row cotton for the Trans-Pecos Area. Proceed. Western Cotton Production Conf.

Jensen, M. E. (ed.). 1973. Consumptive Use of Water and Irrigation Water Requirements. Amer. Soc. of Civil Eng. New York, N. Y.

Longenecker, D. E., E. L. Thaxton, Jr., J. J. Hefner, and P. J. Lyerly. 1970. Variable row spacing of irrigated cotton. Texas Agric. Expt. Sta. Bull. 1102.

Longenecker, D. E., and P. J. Lyerly. 1959. Some relations among irrigation water quality, soil characteristics and management practices in the Trans-Pecos Area. Texas Agric. Expt. Sta. MP 373.

Longenecker, D. E., E. L. Thaxton, Jr., and P. J. Lyerly. 1963. Cotton production in Far West Texas with emphasis on irrigation and fertilization. Texas Agric. Expt. Sta. MP 728.

Mackenzie, A. J. 1972. Soil water, and cropping management for successful agriculture in Imperial Valley. pp. 41-45. Proc. of Nat'l Conf. on Managing Irrig. Agric. to Improve Water Quality. U.S.E.P.A. and Colorado State University.

United States Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. U.S. Dept. of Agric. Handbook 60.

IRRIGATION WITH SALINE WATER IN SOUTH TEXAS

Billy W. Hipp [1]

INTRODUCTION

Poor quality irrigation water is a major problem encountered by growers in south Texas and northeastern Mexico. The primary source of irrigation water in the area is the Rio Grande. Water from the river varies in EC from 0.8 to 1.4 mmhos/cm with a SAR of 2 to 4. Well waters with an EC of 1.4 to 4.4 mmhos/cm and a SAR of 2 to 15 are used as supplemental sources of irrigation water during prolonged dry periods and on crops with high water requirements. Most soils of the area are alluvial and range from clays to sandy loams. Mean annual rainfall in the area is 593 mm with peak rainfall periods in May and June as well as August and September. Salt leaching by fall rains appears to be an important factor in sustained crop production in the area. Crops grown following a dry fall and winter may encounter salinity problems. However, other factors contribute to salinity problems. Hipp and Gerard (1973) found that salt accumulation in irrigated vertisols was greater under continuous cotton than continuous sorghum. Because of the rainfall distribution, changing quality of irrigation water, and management practices there is a lack of equilibrium between soils and irrigation water. Longenecker and Lyerly (1959) discussed the salinity hazards from use of saline waters in the Trans-Pecos region of Texas. Gerard and Hipp (1975) indicated that fall rains decreased the leaching fraction required for salinity control under south Texas conditions. Gerard et al. (1960) indicated that poor quality irrigation water could be used for cotton production on sandy loam soil provided proper management practices were followed. Lysimetric studies (Gerard et al., 1976) indicated that water movement was extremely variable in Willacy fine sandy loam soil. In the same lysimeter studies, total salt drainage was found to be mainly a function of drainage volume (Brown et al., 1974).

Studies were conducted to determine the influence of water quality on salt accumulation in a sandy loam soil profile and effectiveness of salt removal from the soil profile by rainfall.

MATERIALS AND METHODS

Field plots (7.6 x 10 m) were established on Willacy fine sandy loam soil. Cotton (Gossypium hirsutum L.) was planted as an indicator crop and as soon as a stand was obtained, salinity sensors were installed at 15, 30, 60, 90, and 120 cm depths in each plot. Irrigation water quality treatments applied were EC 1.2, 2.5 and 4.2 mmhos/cm. SAR values were

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4, 10 and 15 for the 1.2, 2.5, and 4.2 mmhos/cm water, respectively. Salinity sensors were read periodically and data reported are maximum salinity readings after 0, 2, and 3 irrigations and after 32.7 cm of rainfall following the third irrigation.

RESULTS AND DISCUSSION

Prior to irrigation with various water quality treatments, electrical conductivity (EC) in the soil profile, as indicated by salinity sensors, was 1.5 mmhos/cm or less (lower limit of detection of salinity sensors) at 15 to 60 cm (Fig. 1) but ranged from 1.5 to 2.5 mmhos/cm at 90 to 120 cm depth. Two irrigations (10 cm each) with EC 1.2 mmhos/cm water increased soil salinity to 1.9 mmhos/cm (Fig. 2) at 15 and 30 cm depths and 3 mmhos/cm at 90 cm depth. Two irrigations with 2.5 mmhos/cm water increased soil salinity to slightly more than 3 mmhos/cm at depths of 15 to 60 cm but influenced salinity very little at the 90 and 120 cm depths. Irrigation with 4.2 mmhos/cm water increased soil EC to 4.5 mmhos/cm at 15 cm and 3.9 mmhos/cm at 30 cm soil depth (Fig. 2). Salinity was increased to 3 to 4 mmhos/cm at the 60 and 120 cm soil depth when irrigated twice with water having an EC of 4.2 mmhos/cm. Three cms of rain fell between application of the first and second irrigation.

Three irrigations with EC 1.2 mmhos/cm water slightly increased soil salinity over the two irrigations (Fig. 3) but three irrigations with EC 2.5 mmhos/cm water increased soil EC to 4 mmhos/cm at 15 and 30 cm and increased it to 5.5 mmhos/cm at the 60 cm soil depth. There was also an increase at 90 and 120 cm soil depth. Three irrigations with 4.2 mmhos/cm water resulted in soil EC of 7.2, 6, and 5 mmhos/cm at 15, 30, and 60 cm depths, respectively. Rainfall between the second and third irrigation was 3.5 cm. The third irrigation was applied on June 24 and was sufficient for the remainder of the crop year. After the third irrigation there was a 14-day dry period followed by a 12-day rainy period which resulted in 32.7 cm of rain. The 32.7 cm rains reduced soil EC values, particularly at 15 and 30 cm soil depth (Fig. 4). Salinity in soil that had been irrigated with water of EC 1.2 mmhos/cm was 1.5 mmhos/cm at 15, 30, and 60 cm but was 2.5 mmhos/cm at 90 cm and 3.5 mmhos/cm at 120 cm depth. Rainfall reduced soil EC from 4 to 1.8 mmhos/cm at 15 and 30 cm depth in treatments that had received irrigation water with EC values of 2.5 mmhos/cm. Maximum soil EC after rainfall on this treatment was 4.5 mmhos/cm at 120 cm depth. Soil EC was reduced from 7.2 to 2.4 mmhos/cm at the 15 cm depth and from 6 to 3 mmhos/cm at the 30 cm depth following rainfall on soils that had been irrigated with EC 4.2 mmhos/cm water. EC at lower depths in soil receiving this treatment was 4.2, 5 and 6 mmhos/cm at 60, 90, and 120 depths, respectively.

CONCLUSION

Leaching by rainfall is adequate to reduce soil salinity to acceptable levels in south Texas and northeastern Mexico. It allows growers to use more saline water for irrigation that is possible in areas where less leaching by rainfall occurs.

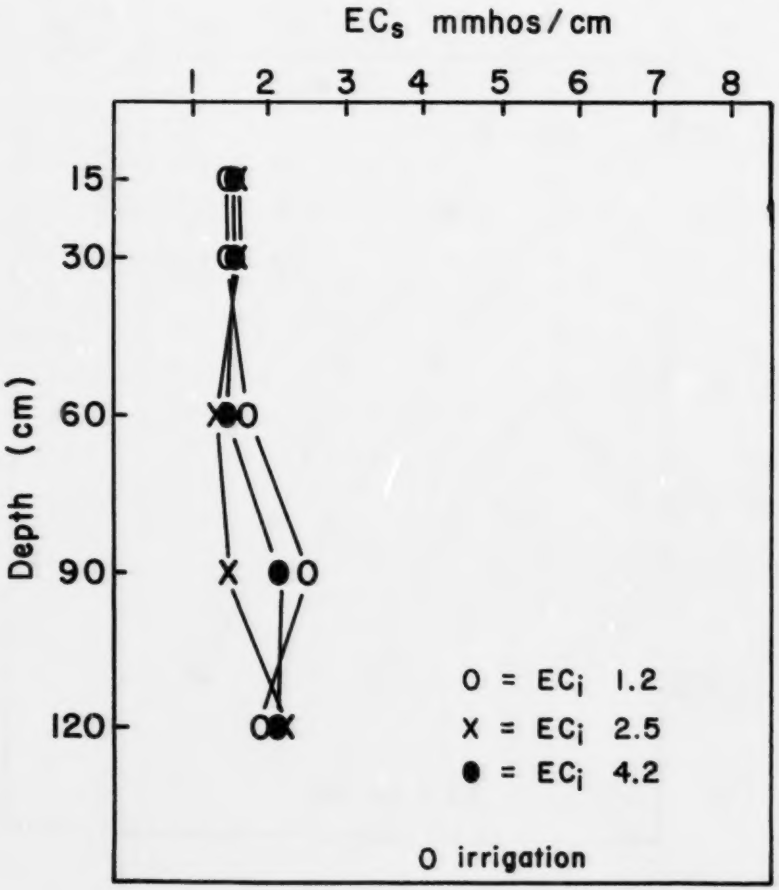

Figure 1. Salt distribution in the soil profile at initiation of the water quality treatments, Rio Grande Valley of Texas.

Source: Texas Agricultural Experiment Stations at Weslaco, Texas.

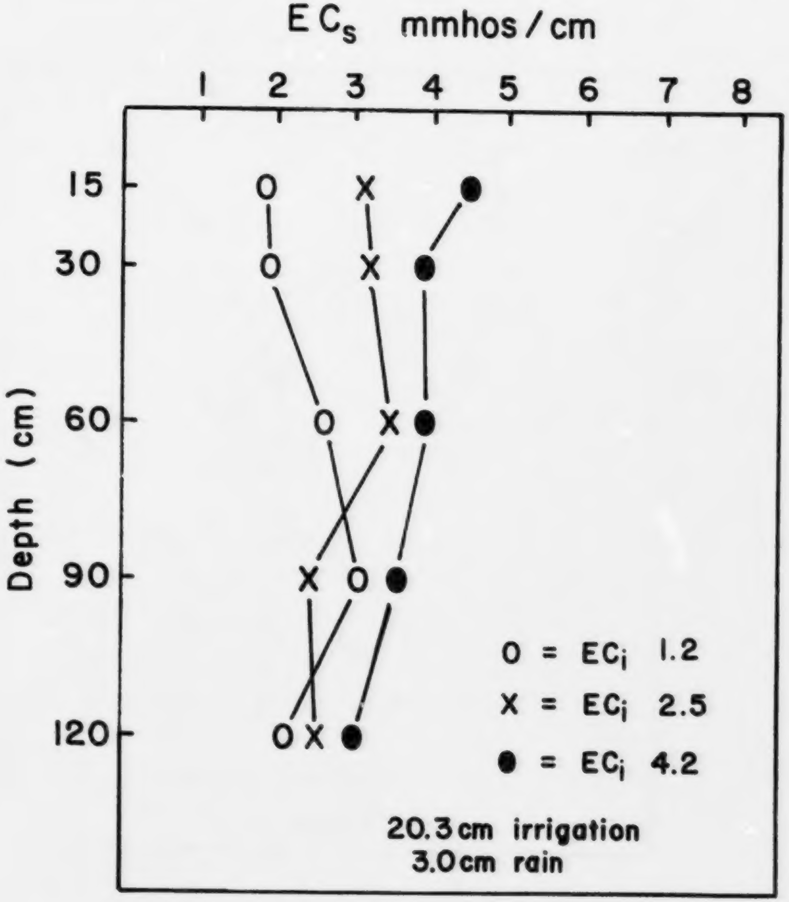

Figure 2. Salt distribution in a sandy loam soil profile after two irrigations with three qualities of water, Rio Grande Valley of Texas.

Source: Texas Agricultural Experiment Station at Weslaco, Texas

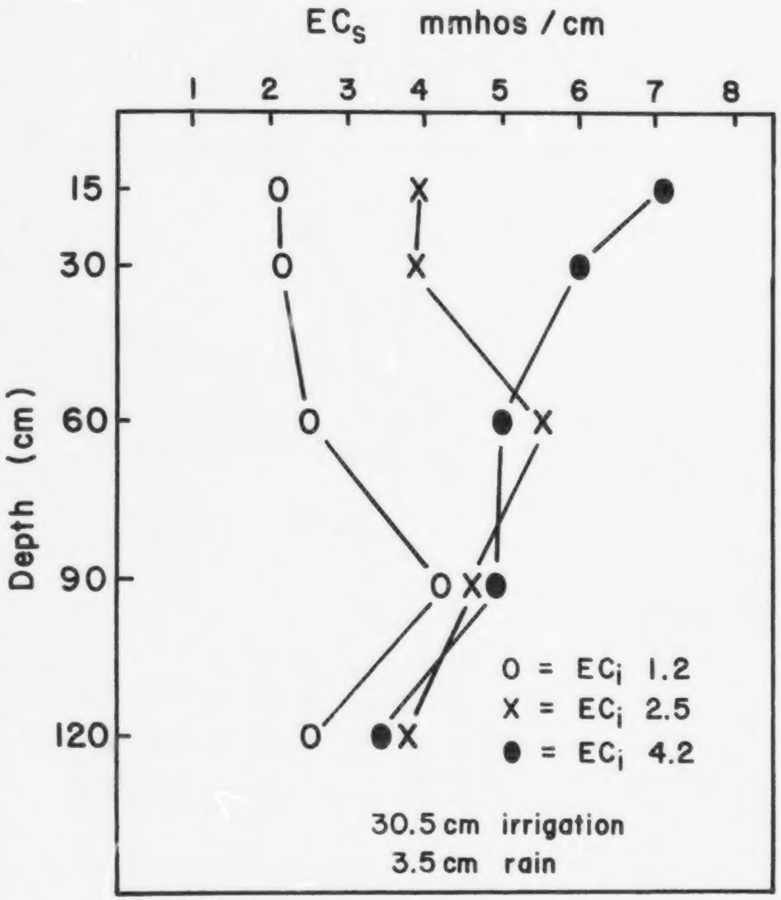

Figure 3. Salt distribution in a sandy loam soil profile after three irrigations with three qualities of water, Rio Grande Valley of Texas.

Source: Texas Agricultural Experiment Station at Weslaco, Texas.

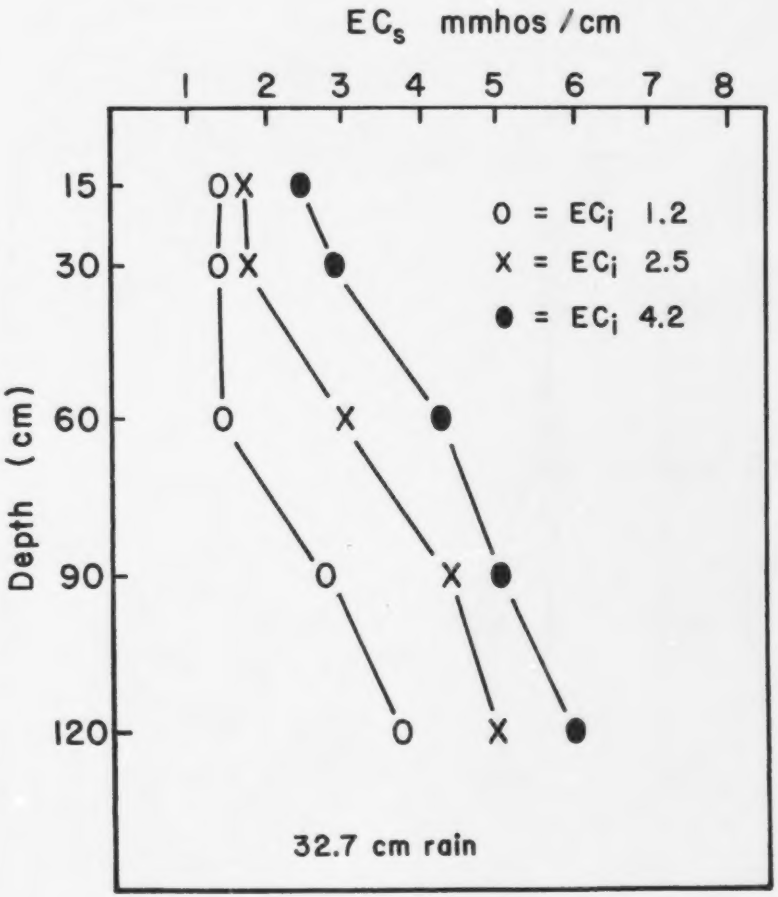

Figure 4. Salt distribution in sandy loam soil after 32.7 cm of rain following 30.5 cm of irrigation water of given qualities, Rio Grande Valley of Texas.

Source: Texas Agricultural Experiment Station at Weslaco, Texas.

LITERATURE CITED

Brown, K. W., C. J. Gerard, D. W. DeMichele, P. J. H. Sharpe and B. W. Hipp. 1974. Investigation of the Return Flow from Irrigated Land. Texas Water Resources Institute, Texas A&M Univ. Technical Report No. 60.

Gerard, C. J., C. A. Burleson, M. E. Bloodworth, W. R. Cowley and J. W. Biggar. 1960. Effect of Irrigation Water Quality and Soil Amendments on Crop Yields and Physicochemical Properties of a Coarse Textured Soil. Tex. Agric. Exp. Sta. MP-624.

Gerard, C. J. and Billy W. Hipp. 1975. Irrigation and Soil Studies on Sugarcane. Tex. Agric. Exp. Sta. TR 75-2.

Gerard, C. J., B. W. Hipp, and K. W. Brown. 1976. Field Investigation of Return Flow from Irrigated Land in South Texas: I. Drainage and Evapotranspiration. Submitted to Agron. Jour.

Hipp, Billy W. and C. J. Gerard. 1973. Influence of Cropping System on Salt Distribution in an Irrigated Vertisol. Unpublished.

Longenecker, D. E. and P. J. Lyerly. 1959. Chemical characteristics of soils of West Texas as affected by irrigation water quality. Soil Sci. 87:207-217.

GROUNDWATER OF VOYVODINA, ITS QUALITY AND APPLICABILITY FOR IRRIGATION

B. Živković [1]

INTRODUCTION

Agricultural production in Voyvodina (Fig. 1) has the potential of becoming the leading economic factor in the area. This potential is due to the favorable natural conditions existent in that area, mainly, the relatively favorable climatic conditions; large areas of land possessing good physical, chemical and productional features; the flatness of the region and the possibility of effective application of modern agricultural equipment; large-scale application of modern agrotechnical measures with introduction of new high yielding varieties of agricultural crops; and a profusion of well water which can be used for irrigation.

Special attention has been paid to the underground water of Voyvodina in the last three decades, and this has been done from various aspects. Numerous problems were solved which were important from a scientific as well as a practical point of view.

This paper will attempt to give detailed information about the up-to-date results obtained in investigations of the problems of the groundwater in Voyvodina and its applicability for irrigation, and to point out some current and important problems which have to be solved in the future.

WATER QUALITY CLASSIFICATION

The first investigations made on the suitability of surface and groundwater for irrigation were started by Nejgebauer (1949b). Using foreign investigators' experience, especially those from the Soviet Union and America, Nejgebauer made a temporary classification of irrigation water in Voyvodina. The classification consisted of four major classes and ten subclasses. The advantage of this method of classification is that it presents the total salt content and the ratio of divalent cations (Ca^{++} and Mg^{++}) to monovalent sodium.

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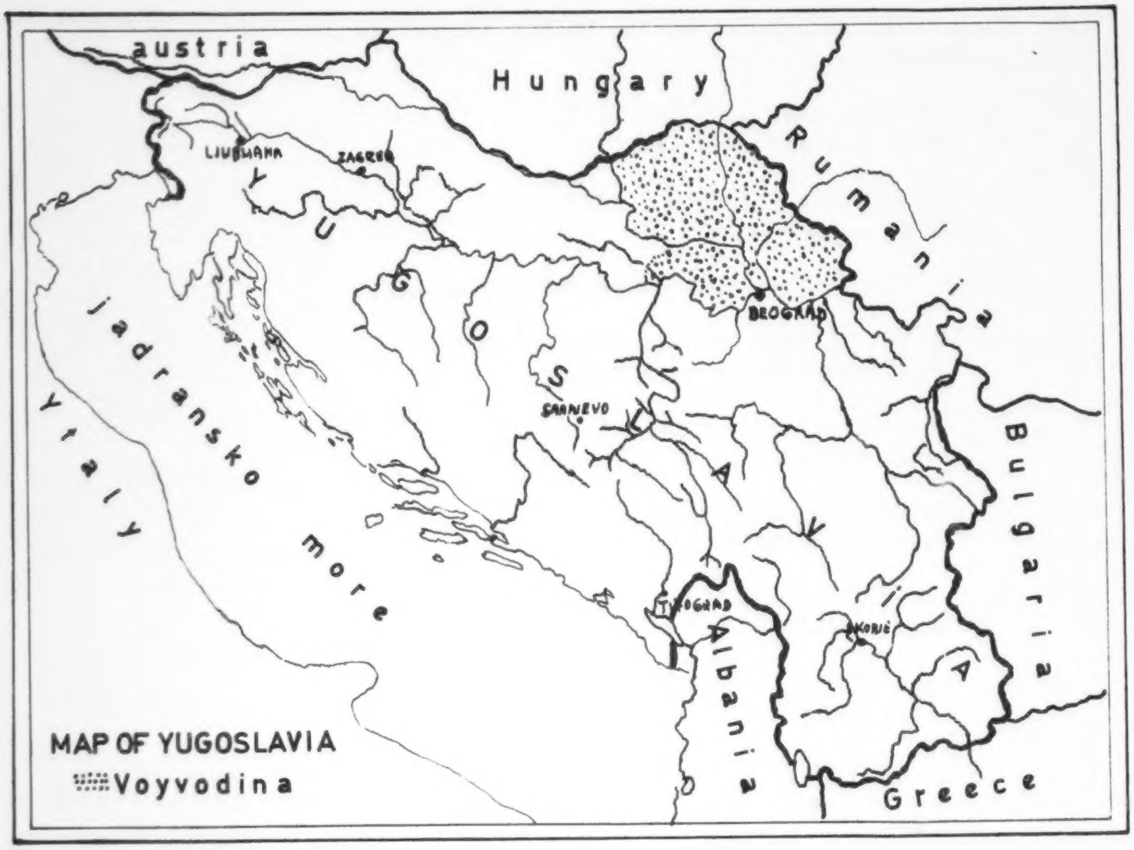
austria
Hungary
YUGOSLAVIA
Rumania
LJUBLJANA
ZAGREB
BEOGRAD
SARAJEVO
Jadransko more
Ytaly
Bulgaria
TITOGRAD
SKOPJE
Albania
Greece
MAP OF YUGOSLAVIA
Voyvodina

Figure 1: Location of Voyvodina

CLASSIFICATION OF IRRIGATION WATER IN VOYVODINA

Prof. V. Nejgebauer

I. Excellent water especially suitable for leaching of saline depressions.

  A. Solid residue is less than 700 mg/l.
  Ratio Ca+Mg:Na+K is higher than 3.

  B. Solid residue is less than 700 mg/l.
  Ratio Ca+Mg:Na is higher than 3.

II. Good irrigation water.

  A. Solid residue is less than 700 mg/l.
  Ratio Ca+Mg:Na is higher than 1 but less than 3.

III. Water with irrigation applicability subject to testing under field conditions.

   A. Solid residue 700-3000 mg/l.
      Ratio Ca+Mg:Na is higher than 3.

   B. Solid residue 700-3000 mg/l.
      Ratio Ca+Mg:Na is higher than 1.

IV. Water which is not applicable for irrigation.

   A. Solid residue is less than 700 mg/l.
      Ratio Ca+Mg:Na is less than 1.

   B. Solid residue is 700-3000 mg/l.
      Ratio Ca+Mg:Na is less than 1.

   C. Solid residue is higher than 3000 mg/l.
      Ratio Ca+Mg:Na is higher than 3.

   D. Solid residue is higher than 3000 mg/l.
      Ratio Ca+Mg:Na is higher than 1.

   E. Solid residue is higher than 3000 mg/l.
      Ratio Ca+Mg:Na is less than 1.

Studying the critical depth of salty groundwater and the danger of secondary salinization of the soil in Voyvodina, Nejgebauer (1949a) stated that the critical level of moderately salinized water is at 250 cm and that of slightly mineralized water is at 200 cm beneath the soil surface.

GROUNDWATER STUDIES

Investigating the quality of irrigation well water on the territory of Voyvodina for a longer period of time, Živković (1954, 1956) collected data which was used to divide the province into different regions according to the content of total salt in the water in both the spring and autumn seasons, as well as according to the chemical composition of those salts. The level of groundwater in the examined wells changed, depending on rainfall quantity, relief, and surface hydrography. With higher rainfall and higher water level of rivers and canals, the groundwater level rose to the soil surface, dropping again during dry periods. The groundwater level is regularly higher in the first period of observation (March-April) than in the second period (September-October).

The total quantity of solid residue per liter of water is somewhat higher in most of the wells at high groundwater level, i.e., in the first period.

Groundwater Regions

During the investigation, it was determined that some groups of wells contained water of different composition than others. Therefore, the total system of tested well waters was divided into six regions.

The region of Srem has mostly good irrigation water. The total content of solid residue in the groundwater of Srem is within the limit of 450 to 1500 mg per liter.

The region of Tamiš-Dunav contains approximately 800 to 1500 mg of solid residue per liter of water. The water of this region contains mostly sodium chloride and sodium sulfate, which should not be used for irrigation.

The region of Banat is characterized by the content of solid residue of 500 to 3000 mg per liter of water; some waters contain over 5000 mg per liter of solid residue. The salts present are mostly sodium chloride and sodium sulfate.

The region next to the Tisza River contains dissolved salts of from 500 to 3000 mg per liter. Wells which are not influenced by the water from the Tisza River have a high content of solid residue (over 6000 mg per liter). The composition of the dissolved salts is mostly sodium sulfate. Only groundwater connected underground with water from the river can be used for irrigation and, even then, only with a constant control of the chemical composition of the irrigated soil.

The region by the Danube River has groundwater with the lowest content of solid residue, an average of 500 to 1000 mg per liter. The abundance of calcium and magnesium over sodium, and the relatively small content of total water soluble salts makes this water very favorable for irrigation.

The region of middle Bačka contains soluble salts in the groundwater of between 500 to 2000 mg per liter, but in most cases about 1500 mg per liter. The central and northern parts of southern Bačka have groundwater with solid residue content of over 2500 mg per liter. This water contains mostly sodium bicarbonate, sodium sulfate, and sodium chloride, and, therefore is not suitable for irrigation.

Salinization Hazard

Investigating the groundwater of Voyvodina for soil salinization, Živković (1964, 1965, 1972) brought forth his results concerning this important problem.

The intensity of soil salinization in Voyvodina is determined by various factors but mostly by the water level and chemical composition of the groundwater, especially during the vegetation season when the average daily temperature and evapotranspiration are high.

The observation of the level of groundwater from the surface peak elevation was recorded three times a month during the period from 1951-1970. The maps showing the level of groundwater were drawn for the growing season (April-September) as well as for the autumn-winter period (October-March). At the same time samples of water from a system of 56 wells were taken and samples from soil profiles, for pedological investigations, were tested.

The ability to determine those areas which have high groundwater level, i.e., level up to 200 cm below the soil surface, during the period of April-September is of special significance. The groundwater in Voyvodina begins to rise from March and has its maximum height in June-July. It decreases at the end of June or during July and its minimum is reached in October-November, sometimes in December; the total area which has a groundwater level limit of up to 150 cm during the period of April-September is 43,025 ha, while 313,550 ha have a level of 150-200 cm. It is evident that areas with groundwater level up to 200 cm are large enough that the problem of soil salinization deserves some serious consideration.

Table 1. Review of the average groundwater level in Voyvodina from 1951-1970.

Ground water level in cm.	April-September ha	October-March ha
Up to 100	97,400	2,530
100-150	340,625	46,120
150-200	313,550	219,080
200-250	384,575	388,150
250-300	312,925	383,670
below 300	701,755	1,111,280

According to Kovda (1947), mineralization and chemical composition of groundwater are affected by the composition of the substrate through which the water flows, the speed at which the groundwater flows, the intensity of evaporation, and transpiration.

By testing the oil wells in Voyvodina it was shown that salty groundwater is present in nearly all geological formation. Moreover, it was observed that the chemical composition of the water from the artesian wells differs with the different depths to which the wells are drilled. For example, the water from an artesian well in Coka, with a depth of 400 m, has 1152 mg of total salts per liter, and most of the salts present are in the form of $NaHCO_3$ (1055 mg), with a small amount of NaCl (10 mg) and few traces of Na_2CO_3. At the same time, water tested in Sajan, at a depth of about 250m, had a very small content of salts (only 386 mg/liter), and the salts present consisted of $NaHCO_3$ (95 mg.), NaCl (152 mg.), Na_2SO_4 (21 mg.) and Ca+Mg $(HCO_3)_2$ (115 mg.).

The salt content of the groundwater of Voyvodina is variable with a range of 221-5360 mg per liter, mainly however, there are some exceptions. For example, one of seven samples of groundwater tested near the town of Kikinda, in October 1967, contained 10,607 mg of solid residue per liter while a second sample contained 15,370 mg of salts per liter. The remaining five samples of groundwater contained over 4,000 mg of water dissolved salts per liter. The salt composition consisted of NaCl, $NaHCO_3$, and Na_2SO_4 in decreasing order, with small quantities of Na_2CO_3. The content of magnesium and calcium salts is considerably less than the content of sodium salts.

The salt content in the groundwater of the loess terrace of Bačka is up to 3,600 mg per liter. The salt content of the groundwater in the central part of southern Bačka consists mostly of $NaHCO_3$ (up to 1.500 mg per liter), NaCl (up to 850 mg per liter), Ca+Mg$(HCO_3)_2$ (up to 500 mg per liter), Na_2CO_3 and Na_2SO_4. Therefore, in this part of Voyvodina the salinization hazard is mostly of the carbonate-sodium type.

The groundwater in the largest part of Srem, because of its depth, generally is not a threat to salinization of the soil under the present conditions.

We have shown by our investigations that the salt ratios in the groundwater of Voyvodina change with the change in the degree of mineralization. Water with a lower degree of mineralization (up to 700 mg/liter) contains mostly sodium bicarbonate and very little neutral salts. The rise in the degree of mineralization results in a relative decrease in the $NaHCO_3$ and Ca+Mg$(HCO_3)_2$ content and an increase in neutral salts content. In the water samples containing over 5,000 mg/liter of dissolved salts, a high percentage of NaCl is observed. Thus , for example, in the sample of water from the surroundings of Kikinda,which possesses 15,370 mg/liter of salts, the content of NaCl is 5,248 mg/liter.

The chemical composition of the artesian well water was tested by Kukin (1965) who stated that only 3 wells out of 32 tested possessed water where Ca+Mg exceeded Na+K, while 29 wells have water with a remarkable excess of Na+K over Ca+Mg. Of the anions in the water of the 29 wells, the bicarbonate ion prevailed and the Cl ion was present in three samples only.

APPLICABILITY OF GROUNDWATER FOR IRRIGATION IN VOYVODINA

On the basis of our investigations and results of other investigations, the groundwater of most of the areas in Voyvodina has been shown to be high in total dissolved salts and, therefore, represents a potential hazard when used for irrigation. The cation composition of the salts (Ca+Mg and Na) is usually unfavorable, so if this water is used for irrigation the possibility of exchangeable sodium accumulation in the soil should not be ignored. The intensity of the soil salinization in the natural conditions of Voyvodina, and the usage of water with unfavorable chemical composition, does not depend solely on the water quality but on other factors as well: natural soil features, applied agrotechnical measures, the varieties of plants which are irrigated, the watering schedule and the depth of the groundwater.

The salt and sodium hazard present in Voyvodina groundwaters is illustrated by conditions that developed in a chernozem soil that had been irrigated for ten years while vegetable crops were grown. The irrigation water had a salt content of 1,281 mg/l and a ratio of Ca+Mg to Na of 0.01. The salts consisted mainly of $NaHCO_3$ (1,054 mg/l), followed by NaCl (105 mg/l) and Na_2CO_3 (37 mg/l). Due to the salinity of the irrigation water, the chernozem soil now resembles a Solonchak. Morphological changes resulting from the process of secondary salinization are evident on the deterioration of the soil structure, with a consequent worsening of aeration. The puddled condition of the soil surface is another indictation of the deterioration. Very hard clods form when the plow layer is dry.

In recent years, groundwater use for irrigation has been increasing, especially on the loess terrace in Bačka. It seems likely, considering the quality of the irrigation water, that the area of Solonchak and Solonetz soils will increase markedly. At present there are 106,622 ha of Solonchak and Solonetz soils in Voyvodina, all of which is used exclusively for low-yielding pastures.

The only groundwater that can be used for irrigation without any danger of secondary salinization is that found within 2 to 3 km of the Danube, Sava, and Tisza rivers. Those waters have a favorable chemical composition and the soil there is permeable and has good natural drainage. With poor management, however, even these areas could become salinized.

Farmers in some part of Voyvodina continue to use poor quality groundwater for irrigation. They do so without an understanding of the threat such water has on the future productivity of the land. It is important to bear in mind that the process of soil salinization cannot usually be observed visually for a year or two after the use of poor quality water has begun. The farmers-and some agricultural engineers-are so preoccupied with increasing crop production that they neglect the salinity problem. That neglect can be very costly since once a soil is salinized it is very difficult, and sometimes impossible to restore the favorable features the soil had before salinization. The fact that there are saline spots in the midst of the best chernozem and chernozem-like meadow soils demonstrate how serious the problem can be.

The shortage of rain during the time when crops experience their fastest growing period and when evapotranspiration is greatest represents a severe limitation to crop production in Voyvodina in some years. Irrigation is an obvious solution to the problem but a major question is whether poor quality groundwater should be used when there is a profusion of excellent quality river water. The decision should be a social one and not simply a technical one.

CONCLUSION

On the basis of the results achieved in groundwater investigations and their applicability in Voyvodina the following conclusions can be made:

1. Groundwater in Voyvodina is mostly of poor quality, has a relatively high content of dissolved salts, and should not be used for irrigation.
2. Underground water in the watersheds of the Danube, Tisza and Sava can be used for irrigation due to their good quality.
3. In order to prevent further soil salinization it is necessary to lower the groundwater level to a harmless depth which, due to the natural conditions in Voyvodina, is 200-250 cm.
4. It is important to provide expert control both over the usage of the groundwater for irrigation and the control of soil salinization.

LITERATURE CITED

Kovda, V. 1947. Procesi sovremenogo solenakuplenija (galogeneza) v počvah i vodah. Počvoved. No.11. Moskva.

Kukin, A. 1965. Les eaux artesiennes a Bačka (Bassin Panonique). Reunion de Hannover. Association internationale des hydrogeologues.

Nejgebauer, V. 1949a. Upotrebljivost površinskih i podzemnih voda za navodnjavanje i njihova klasifikacija u prirodnim prilikama Vojvodine. Radovi polj. naučnoistraživač. ustanova, knj.1. Beograd.

Nejgebauer, V. 1949b. Kritični nivo podzemnih voda u Vojvodini i opasnost od sekundarnog zaslanjivanja. Radovi polj. naučnoistraz. ustanova, knj.1. Beograd.

Živković, D.M. 1954. Ispitivanje kvaliteta bunarske vode za navodnjavanje na teritoriji Vojvodine. Zemljište i biljka, No. 1-3, Beograd.

Živković, D.M. 1956. Kvalitet bunarske vode i navodnjavnje na teritoriji Vojvodine. Poljoprivreda Vojvodine, br. 12, Novi Sad.

Živković, B. 1964. Podzemne vode Vojvodine kao faktor zaslanjivanja zemljišta. Zemlijište i biljka, No. 2. Beograd.

Živković, B. 1965. Problem zaslanjivanja zemljišta i uporedne karakteristike normalinih zemljišta, zemljišta u zaslanjivanju i solončaka u Vojvodini. Savremena poljoprivreda Sv. 5, Novi Sad.

Živković. B. 1972. Podzemne vode i njihova upotreblijivost u Vojvodini. Prvi kongres o vodama Jugoslavije, knjiga I. Beograd. p. 117-121.

POTENTIAL FOR SALINE WATER IRRIGATION OF TROPICAL SOILS[1]

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INTRODUCTION

The concentration and composition of ionic constituents in irrigation water are known to have profound effects not only on crop growth but also on the chemical and physical properties of soils. When a soil has been irrigated with a given water for a sufficiently long time, a dynamic chemical equilibrium takes place between water and soil. This produces fluctuating patterns for the concentration of soil solution and distribution of exchangeable ions between the absorbed and solution phases. Soil physical properties may, or may not, be affected by the nature of such chemical equilibrium depending on both the water and the soil under consideration. Crop considerations set aside, the effects of a given water on both the chemical and physical properties of a given soil provide the fundamental criteria for judging whether the water is suitable for irrigation use on the soil.

Voluminous data are now available on the nature of chemical reactions in general and cation exchange equilibria involving temperate soils and irrigation water in particular (Rhoades, 1974). Effects of water quality on the physical properties of temperate soils also have been the subject of many investigations (McNeal, 1974). However such information is scant for tropical soils. Preliminary studies have been previously reported on the effects of saline water treatments on both the chemical properties and physical responses of selected Hawaii soils (El-Swaify and Swindale, 1963 and 1970; El-Swaify, 1970; Sinanuwong and El-Swaify, 1974).

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Trends obtained in those studies indicate that available information on arid temperate soils is not applicable to tropical soils. In this paper we report results of investigations on soils representing all major irrigated or irrigable soils in Hawaii to define their tolerance limits for irrigation with waters of various salinities.

MATERIALS AND METHODS

The Soils

Soils were selected based on their requirements for and suitability for irrigation in Hawaii and also because they might be representative of irrigable soils in other areas of the Tropics. The soils belong to the orders Aridisols (Kawaihae very fine sandy loam), Mollisols (Ewa clay), Oxisols (Molokai silty clay), and Vertisols (Honouliuli clay and Lualualei clay), Soil Survey Staff (1975). Surface samples were collected to represent the top 40 cm (plow layer) of cultivated soils and the top 15 cm (within the A_1 horizon) of other soils. Samples from defined subsurface horizons were also investigated in certain parts of this study. Table 1 is a summary of the classification and important characteristics of the soils. Note that kaolins, sesquioxides of iron and aluminum, and amorphous silicates are the dominant inorganic constituents of most of the soils.

Experimental Procedures

Cation exchange equilibria were investigated at 0.01 and 0.10 N concentration levels in batches containing homoionic soils and chlorides of Na^+ and Ca^{++} or Mg^{++}. The method was exactly as described by Sinanuwong and El-Swaify (1974). Regression constants (a and b) and the correlation coefficient (r) for the equation

$$ESR = a + b\ SAR$$

were calculated using continuous simple regression analysis. In this equation ESR is the exchangeable sodium ratio q_{Na}/q, and SAR is the sodium adsorption ratio, $C_{Na}/(C/2)^{\frac{1}{2}}$, where q_{Na} represents the exchangeable Na at equilibrium in meq/g, q the exchangeable divalent cation in meq/g, C_{Na} the concentration of Na in the equilibrium solution in meq/ℓ, and C the concentration of divalent cations in the equilibrium solution in meq/ℓ.

Saturated hydraulic conductivities were determined on undisturbed soil cores of 7.6 cm length and 10.7 cm outside diameter. The cores were collected by a special sampler which consists of an outer auger rotating around a stationary collection tube (Andrews and

(TABLE 1)

Summary of soil classification and characteristics of surface samples.

Soil and current use #	Family classification according to taxonomy	Mean annual rainfall cm	Dominant minerals*	Organic matter %	Specific surface area** m^2/g	Clay %	pH†	CEC‡	H** cm/hr
Kawaihae(U)	Medial isohyperthermic Typic Camborthids	13	A,K,He,Mh,M	0.83	152	41	7.1	19	3.6
Ewa(C)	Fine halloysitic isohyperthermic Aridic Haplustolls	61	K,A,He,G_i,G	2.6	105	65	6.8	18	5.4
Molokai(C)	Clayey kaolinitic isohyperthermic Typic Torrox	75	K,G_i,G,He,Mh	0.83	104	78	6.4	15	4.7
Honouliuli(C)	Very fine kaolinitic isohyperthermic Typic Chromusterts	51	K,A,He,G_i,O	1.3	173	58	7.0	31	18.5
Lualualei(I)(U)	Very fine halloysitic isohyperthermic Typic Chromusterts	38	K,I,A,G_i,G	0.72	239	82	7.1	39	10.8
Lualualei(II)(U)	Very fine montmorillonitic isohyperthermic Typic Chromusterts	40	S,F,G,He,Mh	1.61	308	71	7.3	69	----

Soil under cultivation (C) or uncultivated (U)

* Listed in decreasing order of abundance (A = amorphous silicate, F = feldspars, G = goethite, G_i = gibbsite, K = kaolins, He = hematite, I = interstratified 2:1, M = magnetite, Mh = maghenite, O = olivine, S = smectites).

** By ethylene glycol method of Mg-saturated samples.

† In saturated soil paste.

‡ Cation exchange capacity in meg/100 g based on retained Mg^{++} by Mg-saturated samples.

** Saturated conductivity with reference 1 N $CaCl_2$ for undisturbed cores (average of 3-8 determinations).

Broadfoot, 1958). Chemical equilibrium with applied solutions was allowed to occur before steady state flow data were recorded (El-Swaify and Swindale, 1968). Leaching with 1N $CaCl_2$ preceded all measurements, and hydraulic conductivities measured with this solution on a given core were used as a basis for computing effects of other solutions. For experiments with homoionic soils, solutions with concentrations of 0.61, 0.12, and 0.012N were applied after 1 N $CaCl_2$ in the sequence $CaCl_2$, $MgCl_2$, KCl, and NaCl. The same core was used for the full sequence whenever possible. Three to five replicate cores were used for each sequence. For experiments with mixed ionic soils, solutions with high proportions of divalent cations were applied first. To suppress biological activity in the soil during the experimentation, 50 ppm of $HgCl_2$ were added in solutions of high salinity (1 N) and 5 ppm in solutions of low salinity (1<N).

Swelling was measured using compressed 1 g samples of homoionic salt-free soils with the technique of El-Swaify and Emerson (1975). Prewetting overnight at 100, then 50 cm suctions preceded swelling measurements at 10 cm suction. A seven-day period was sufficient for equilibrium at this suction over all of the solutions.

The effects of exchangeable sodium or potassium on soil dispersion were measured at 0.10 N electrolyte concentration using homoionic soil mixtures and chloride solutions, resulting in exchangeable sodium percentages (ESP) or exchangeable potassium percentages (EPP) of 0, 5, 10, 15, 25, 50, 75, and/or 100. After appropriate settling times were allowed, the concentrations of clay-sized particles were determined by means of a standardized turbidimeter.

RESULTS AND DISCUSSION

Soil Affinities for Na^+ and Divalent Cations.

Cation distributions in soil solutions and on the exchange complex at equilibrium were used to construct cation exchange isotherms as described by Sinanuwong and El-Swaify (1974). As an example, the Ca-Na and Mg-Na exchange isotherms for the surface horizon of Ewa (Mollisol) soil are shown at two levels of electrolyte concentration in Fig. 1. This figure shows the trends, noted for most of the surface soils, that the affinity for adsorption of Na^+ increases with increasing electrolyte concentration and when Mg^{++} rather than Ca^{++} prevails as the competing cation. When equilibrium studies were initiated using divalent-saturated samples (di-monovalent exchange) the soil exhibited less preference for Na^+ than when Na-saturated soil was used (mono-divalent exchange). Isotherms were similarly obtained for surface horizons of all soils in the study.

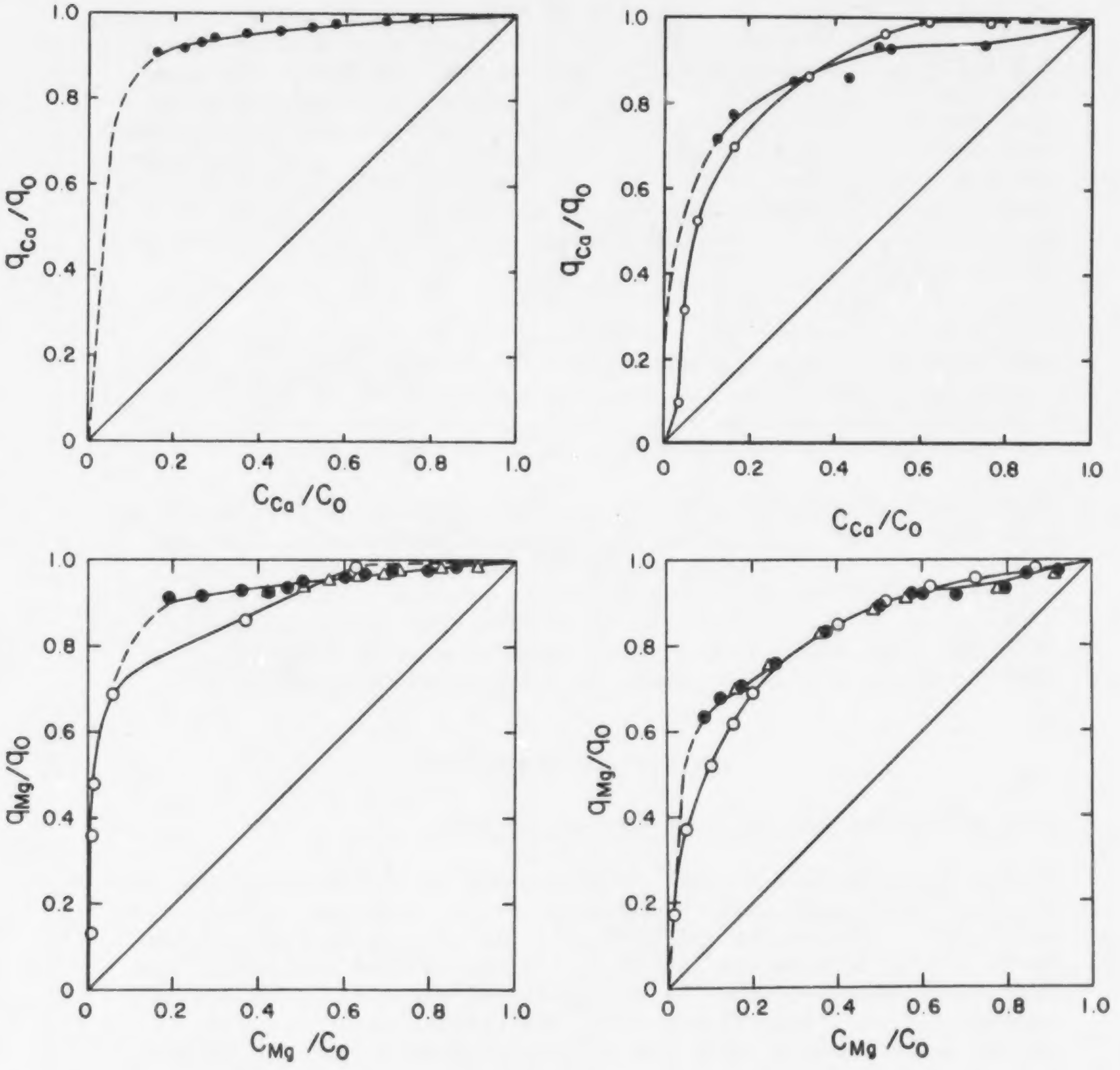


Fig. 1. Ewa (Mollisol) soil isotherms for Ca-Na and Mg-Na exchange at 0.01 N (left and 0.1 N (right) chloride concentrations. Closed and open circles represent di-monovalent and monodivalent exchange, respectively (see test). Triangles represent data obtained by analyzing for both competing ions.

The equilibrium data were analyzed in various ways to quantitatively express the relative affinities of soils for the competing cations. Of most interest here is testing the linear relationship between the sodium adsorption ratio (SAR) and exchangeable sodium ratio (ESR) for each of the soils. Definite differences in the regression constants of the equation ESR = a + b SAR are present not only among the studied soils but also between soil horizons, electrolyte concentrations, and the prevailing competing cations (Sinanuwong and El-Swaify, 1974). Only differences between surface soils are emphasized here. Table 2 lists the regression constants in the above equation combined for all di-monovalent equilibria and specified concentrations. Sample calculations of exchangeable sodium ratios are shown at three SAR levels to illustrate differences among the soils. A linear relationship between ESR and SAR was generally obtained. The order in which this linearity was observed, based on the magnitudes of correlation coefficients, was Ewa > Honouliuli > Kawaihae > Lualualei I > Lualualei II > Molokai. Affinities for Na^+ adsorption not only varied among the soils but also depended on the SAR of soil solution. At low SAR levels (=10) the exchangeable sodium ratios were highest for two of the Vertisols (Lualualei I and Honouliuli), followed by the Aridisol (Kwaihae) and Lualualei II, with the Mollisol (Ewa) and the Oxisol (Molokai) displaying similar affinities. At SAR = 20, only minor differences were noted between the Aridisol, Mollisol, Oxisol, and Lualualei II. The remaining two Vertisols, however, displayed significantly higher Na^+ adsorption. At SAR = 30, Lualualei II and the Aridisol displayed the lowest Na^+ adsorption, with the Oxisol and Mollisol slightly higher and the remaining Vertisols the highest. Differences due to electrolyte concentration levels were second only to differences among soils in affecting Na^+ adsorption; other variables were diferent horizons and competing divalent cations. In general, the ESR calculated at a given SAR level was higher for 0.1 N electrolyte concentration. This is in contrast to findings of Bower (1959), who reported that the linearity of the ESR-SAR relationship is unchanged in the concentration range from 0.05-0.2 N.

The relationship between SAR and ESR at the higher concentration is especially relevant when use of saline water is considered for irrigation. Fig. 2 shows this relationship for Ca-Na exchange up to SAR values of nearly 48 at 0.1 N concentration. Data point calculations are based on combined predictive linear regression equations based on exchange isotherms for all horizons of a given soil. The figure also shows ESR-SAR plots based on the common predictive equations of the U.S. Salinity Laboratory (1954) and Bower (1959), and the equation derived from the diffuse double layer theory (Babcock, 1963). Most data points for the different soils lie below all three predictive plots, particularly at high SAR values, indicating that although these soils vary widely in their affinities for Na^+, as a group, they exhibit lower affinities than do the temperate arid soils for

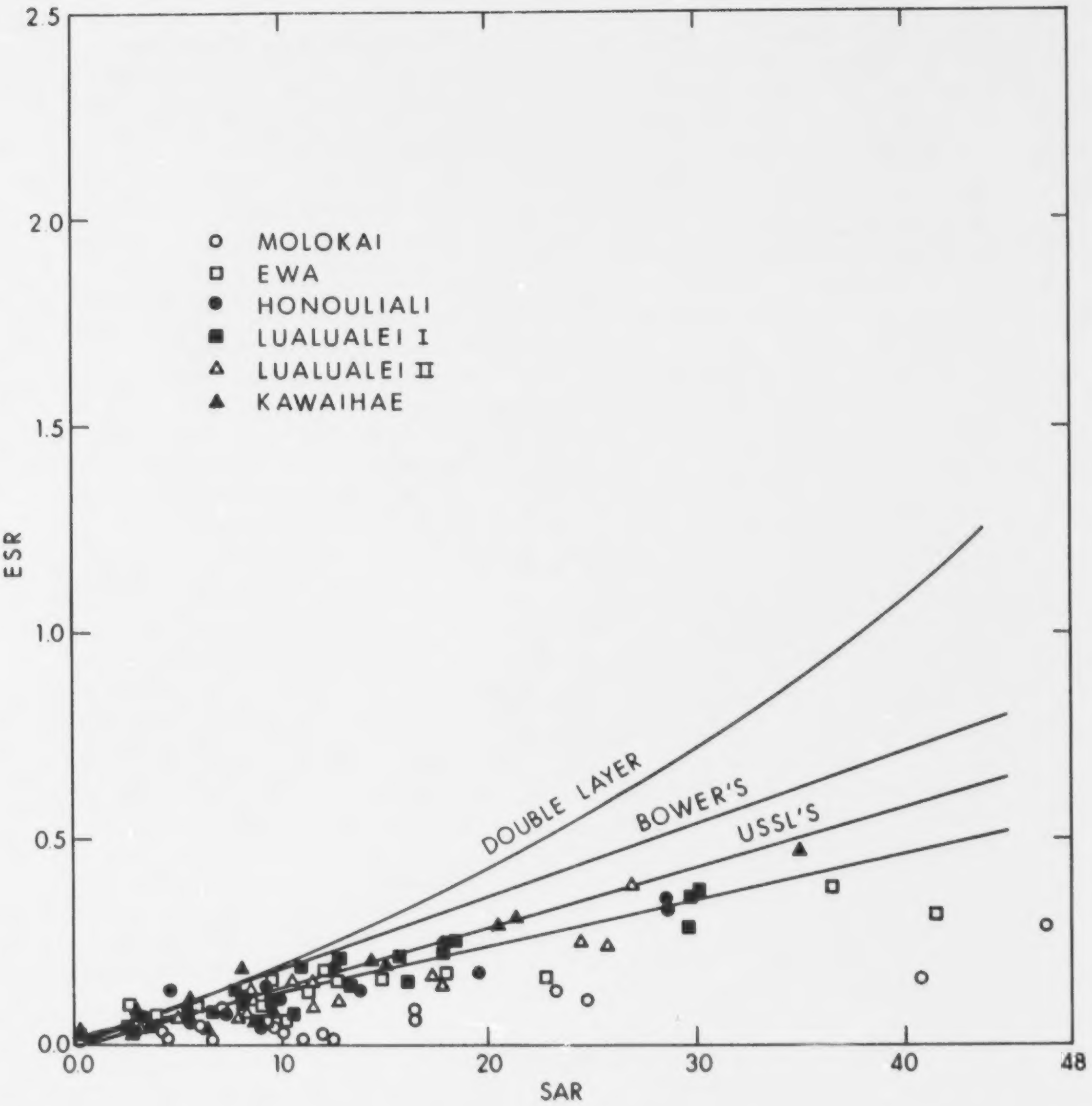


Fig. 2. The relationship between ESR and SAR as predicted by the double layer and empirical equations for 0.1 M Ca-Na exchange. The bottom line represents the overall empirical equation derived in this study.

(TABLE 2)

Regression constants for the relationship ESR = a + b SAR combined for 0.01 and 0.10 N,and calculated ESR values at three SAR levels in soil surface horizons.

				ESR at SAR of		
Soil	a	b	r*	10	20	30
Kawaihae	0.0556	0.0087	0.93	0.142	0.229	0.315
Ewa	0.0025	0.0114	0.97	0.117	0.231	0.345
Molokai	0.0061	0.0112	0.81	0.118	0.230	0.342
Honouliuli	-0.0194	0.0179	0.95	0.160	0.339	0.518
Lualualei I	-0.0282	0.0197	0.91	0.169	0.366	0.536
Lualualei II	0.0424	0.0086	0.87	0.128	0.214	0.300

* correlation coefficient

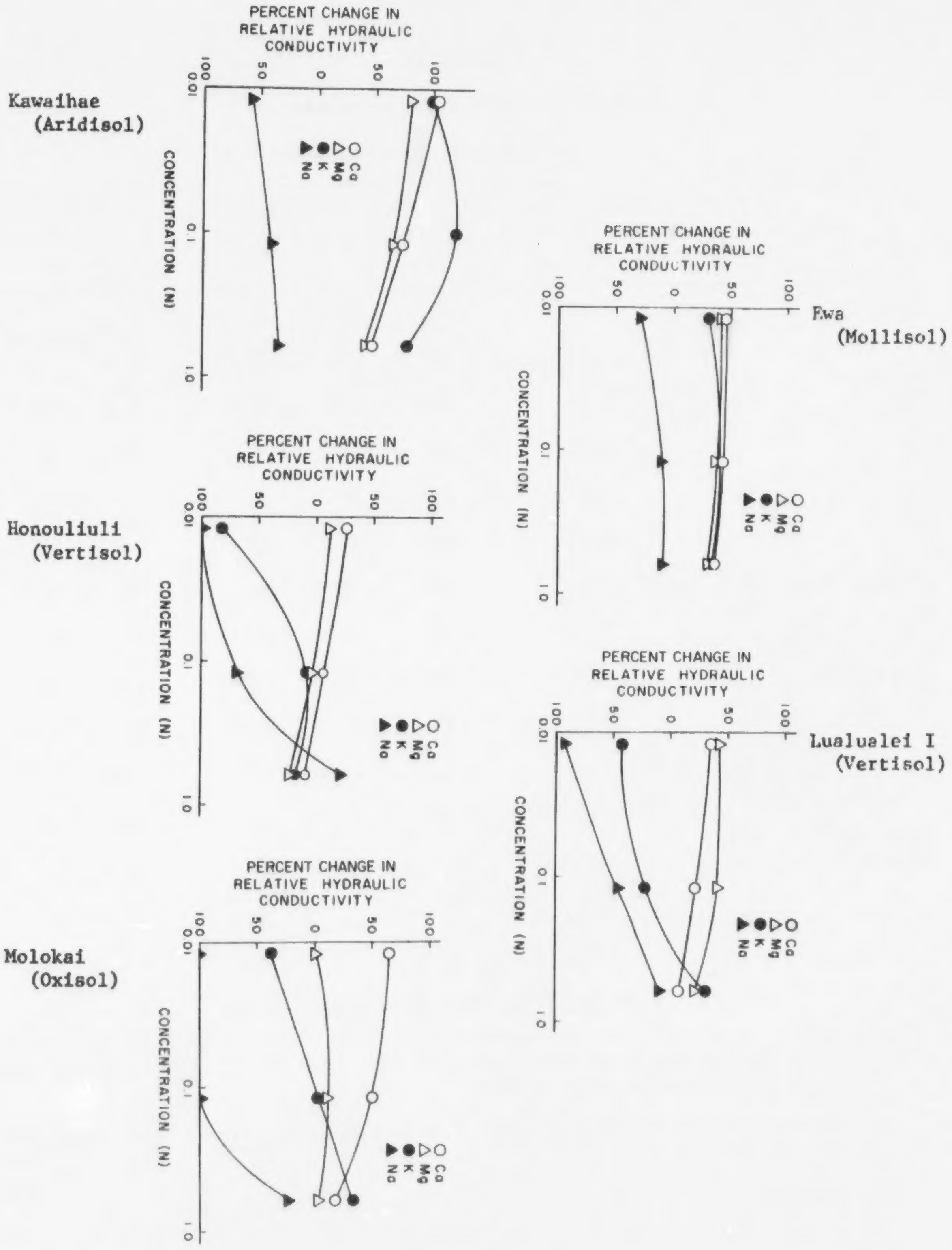
which these equations are known to be successful. The over all empirical equation derived in this study was

$$ESR = 0.021 + 0.011\ SAR$$

and is represented by the bottom line in Fig. 2. The correlation coefficient for this equation was 0.86. As indicated in Table 2, however, and as noted from the scatter of different experimental points the soils can be arranged in the following order of tendency to accumulate Na^+ on the exchange complex: Oxisols $\leq$ Aridisola $<$ Mollisols $<$ Vertisols (except for Lualualei II). The different behavior of the Lualualei II soil appeared to be due to its higher charge density (2.22×10^{-7} meq/cm^2) than for the Lualualei I and Honouliuli soils (1.62×10^{-7} and 1.78×10^{-7} meq/cm^2, respectively). These surface charge densities were calculated from the surface areas and cation exchange capacities as shown in Table 1.

Effects of Exchangeable Na^+ and Salt Concentration on Physical Properties

When the feasibility of saline water irrigation is being evaluated, water transmission characteristics are perhaps the most important soil physical properties to be considered. This is because of leaching requirements whereby excessive water applications are necessary to eliminate salt accumulation and excessive exchangeable sodium in the soil (Rhodes, 1974). As shown in Table 1, saturated hydraulic conductivities for undisturbed soil cores are generally high, ranging from 3.6 cm/hr for Kawaihae soil (Aridisol) to 18.5 cm/hr for Honouliuli (Vertisol). The figures for Vertisols were noticeably higher than expected and were explained by the presence of shrinkage cracks when the cores were collected from a very dry field. It is important, however, to note that the hydraulic conductivities for these soils are much higher than those for soils on which currently available quality standards are based (e.g.,McNeal, 1974). The effects of different cations and solution concentrations on these hydraulic conductivities are shown in Fig. 3. The point of zero change in relative hydraulic conductivity represents the value with the reference 1 N $CaCl_2$ (Table 1). Data above this value reflect increases in saturated conductivity and data below it reflect decreases. Most of the soils displayed some sensitivity to different cation saturations and solution concentrations. In almost every case, increases were noted due to application of $CaCl_2$ and $MgCl_2$ solutions of 0.6 N and lower. This probably reflects the lower viscosities of these solutions than for 1 N $CaCl_2$. Monovalent cation saturations reduced hydraulic conductivities of most soils, particularly at the lowest concentration levels. For K^+,



Kawaihae
(Aridisol)

Ewa
(Mollisol)

Honouliuli
(Vertisol)

Lualualei I
(Vertisol)

Molokai
(Oxisol)

Fig. 3. Changes induced in saturated hydraulic conductivity by different cation saturations and solution concentrations:

(TABLE 3)

Effects of mixed ionic solutions on

relative hydraulic conductivity.

Soils	Divalent cation in mixture	Electrolyte concentration $\underline{N}$	Percent relative hydraulic conductivity* at					
			% exchangeable Na^+ of			% exchangeable K^+ of		
			5	15	60	5	15	60
Kawaihae	Ca	0.10	76	76	69	See footnote **		
		0.01	70	70	70			
Ewa	Ca	0.10	111	120	88	110	121	90
		0.01	65	58	44	72	50	45
	Mg	0.10	107	90	61	See footnote †		
		0.01	100	76	55			
Molokai	Ca	0.1	67	63	56	59	59	89
		0.01	56	53	52	54	51	75
Honouliuli	Ca	0.10	108	98	58	113	95	88
		0.01	76	69	54	89	81	51
	Mg	0.10	111	102	57	118	111	97
		0.01	77	65	47	127	97	81
Lualualei I	Ca	0.10	45	40	14	62	49	60
		0.01	48	40	33	49	43	45
	Mg	0.10	53	50	29	60	55	76
		0.01	0.00	0.00	0.00	80	73	67

* Hydraulic conductivity with divalent-saturated soils (ESP or EPP = 0) were used as basis for computing these values.

** Data not collected because little or no reduction was observed with 100% exchangeable potassium (Fig. 3).

† Not measured.

such reductions were either small (Ewa, Honouliuli, Lualualei I) or absent (Kawaihae, Molokai). Na$^+$ saturation, on the other hand, produced varying degrees of reduction in hydraulic conductivity in every soil. By changing NaCl concentration from 0.6 to 0.012 N, reductions of 20%, 90%, and 25% were noted for the Aridisol, Mollisol, Oxisol, respectively. One hundred percent reduction were noted in both Vertisols and were attained near 0.012 N for the Honouliuli and Lualualei I, respectively, It is apparent, therefore, that Na$^+$ hazards to saturated hydraulic conductivity may be arranged in the order Lualualei > Honoluilui > Ewa > Molokai > Kawaihae. Fig. 4 shows that this is exactly the trend which describes the capacities of different soils to exhibit macroswelling. Na-soils displayed higher swelling than K-soils, which explains, at least in part, more drastic reductions in hydraulic conductivity caused by Na$^+$. Swelling, therefore, reflects the capacity of soil consituents to exhibit sensitivity to irrigation water quality and would provide a useful index for evaluation of Na$^+$ hazard in irrigation water. The principle of threshold concentration (Quirk, 1971) is useful for comparing hydraulic conductivity reductions observed here with those observed for other soils reported in the literature. With full sodium saturation it is noted that reductions of hydraulic conductivity occuring at 0.012 N NaCl were 27%, 85%, 45%, and 100% in the Kawaihae, Ewa, Molokai, and Honouliuli soils, respectively. A 100% reduction was noted in Lualualei soil at 0.12 N NaCl. At nearly the same concentration, Quirk and Schofield (1955) reported reductions of nearly 99% in a soil dominated by illite, kaolinite, and vermiculite. Similarly, McNeal and Coleman (1966) reported reductions of 90-100% in two California soils. It would appear, therefore, that while the Vertisols of this study exhibit threshold concentration requirements similar to those of other arid temperate region (swelling) soils, the remaining soils exhibit higher resistance to sodium effects. The definiton of threshold concentration itself (concentration required to maintain hydraulic conductivities within 25% of the original values) is not sufficiently flexible for many of the soils in this study for which original hydraulic conductivities are much higher than those reported by other workers.

Critical proportions of exchangeable monovalent cations which may present a hazard to hydraulic conductivity can be derived from Table 3. All changes in hydraulic conductivity with varying exchangeable Na$^+$ or K$^+$ are gradual, with little indication of any "threshold" values. The increases in hydraulic conductivity observed in some instances in the presence of small percentages of exchangeable cations are probably due to experimental variability (estimated at ±10% of reported figures) and therefore indicate no change. Certainly it would appear that the value of 15% exchange-

(TABLE 4)

Effects of exchangeable sodium percentage (ESP)
and exchangeable potassium percentage (EPP) on the
dispersion of soils at 0.01 N electrolyte concentration.

	Na-Ca system		Na-Mg system		K-Ca system		K-Mg system	
Soil	ESP	D*	ESP	D*	EPP	D*	EPP	D*
Kawaihae	0	0	-	-	-	-	-	-
	10	0	-	-	-	-	-	-
	15	20	-	-	-	-	-	-
	20	25	-	-	-	-	-	-
Ewa	0	0	-	-	-	-	-	-
	5	0	-	-	-	-	-	-
	10	15	-	-	-	-	-	-
	15	25	-	-	-	-	-	-
Molokai	0	0	-	-	-	-	-	-
	5	0	-	-	-	-	-	-
	10	25	-	-	-	-	-	-
	15	35	-	-	-	-	-	-
Honouliuli	0	0	0	0	0	0	0	0
	5	0	5	0	15	0	15	0
	7	25	10	20	25	15	25	13
	10	50	12	25	33	25	35	23
	15	87	15	43	40	50	45	50
Lualualei I	0	0	0	0	0	0	0	0
	15	0	10	11	5	0	10	0
	25	20	15	25	10	20	15	63
	33	40	18	50	15	23	25	75
	40	50	25	75	25	45	-	-

* D = Dispersed percent of clay-sized particles.

- = not measured.

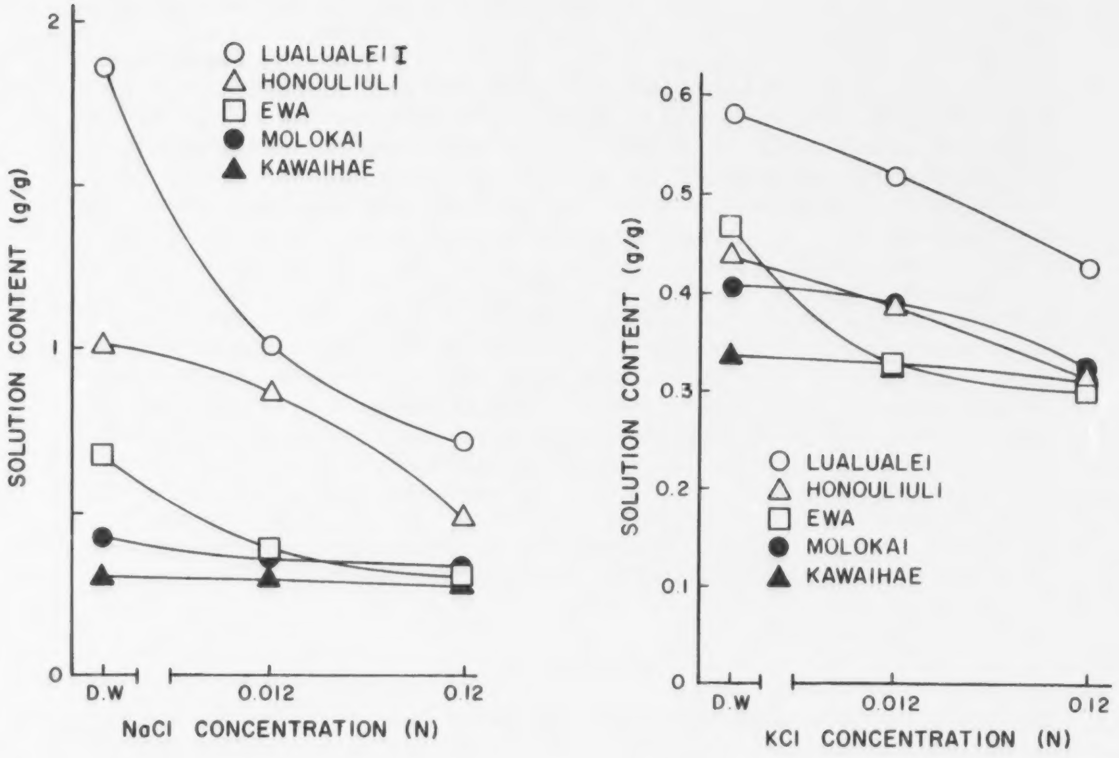


Fig. 4. Swelling of Na-saturated soils (left) and K-saturated soils as indicated by uptake of solutions of various concentrations after equilibrium over 10 cm suction. D. W. refers to distilled water.

able Na^+ (or K^+) has no particular significance for any of the soils. Except for one Vertisol (Lualualei I), hydraulic conductivities remained at nearly 50% or more of their original levels, with exchangeable Na^+ as high as 60%. Based on homoionic soil data, therefore, critical percentages of exchangeable Na^+ in the remaining soils may be assumed to lie near 100% (Fig. 3). Exchangeable K^+ generally caused less reduction than Na^+ with the difference being most notable in the Vertisols. This is most directly attributed to the large difference in macroswelling for the Na^+ and K^+ forms of these soils (Fig. 4). Differences in the degree of dispersion observed at various ESP or EPP values also explained measured differences in hydraulic conductivity. Table 4 shows the effects of ESP values on the disperion of all soils when Ca^{++} is the complementary exchangeable cation, and the effects of ESP and EPP values on the dispersion of Vertisols in the presence of Ca^{++} or Mg^{++} as complementary ions. The ESP required for the beginning of dispersion is in the order Honouliuli < Lualualei I < Molokai ≤ Ewa < Kawaihae. Among the Vertisols, the presence of Ca as a complementary ion induced more dispersion than Mg in Honouliuli but less dispersion in Lualualei. This trend was true for both Na-divalent and K-divalent systems. Enhanced structural breakdown due to Mg has also been reported previously by other authors (Bakker and Emerson, 1973). The dependence of dispersion on exchangeable Na^+ or K^+ followed closely the dependence of saturated hydraulic conductivity, both indicating that the tolerance to structural deterioration due to sodic conditions is highest for the Aridisols, followed by the Oxisols or Mollisols, and is least for the Vertisols. Mineralogical differences, particularly the presence or absence of swelling constituents, account for observed differences.

CONCLUSIONS

The soils in this study generally exhibited less affinity for sodium adsorption and more resistance to structural deterioration due to monovalent cation saturation than is known for irrigated soils in other regions. However, the hazards of developing sodic conditions with saline water irrigation are quite different for the various soils and appear to be in the order of Oxisols ≤ Aridisols < Mollisols < Vertisols. One Vertisol exhibited lower affinity for Na^+ than the other two due to a high surface-charge density and subsequent high preference for divalent cations. The hazard of structural deterioration was also nearly in the same order as above. It may be concluded, therefore, that irrigation with saline water is most feasible for Aridisols and Oxisols, is of moderate feasibility for Mollisols, and is least feasible for Vertisols. The roles played by low swelling clay minerals and by sesquioxides in enhancing soil stability against structural breakdown have been discussed elsewhere (El-Swaify and Emerson, 1975). It must be emphasized, however, that management of such water during actual irrigation is a critical variable for determining ultimate success of its use (Rhoades, 1974).

SUMMARY

The effects of waters with defined salt concentration and ionic composition on the chemical and physical properties of irrigable tropical soils belonging to four Orders were investigated. Studies of cation exchange euilibria indicated that soil affinity for sodium ion adsorption was generally in the order of Oxisols $\leq$ Aridisols $<$ Mollisols $<$ Vertisols. As a group, however, these soils exhibited less tendency to accumulate detrimental sodium ions on the exchange complex than is known for temperate arid region soils. Measurements of hydraulic conductivity showed that soil susceptibility to structural breakdown depended on the presence or absence of swelling minerals. Both hydraulic conductivity reduction and macroswelling were in the order of Aridisols $\leq$ Oxisols $<$ Mollisols $<$ Vertisols. The first two exhibited only minor sensitivity to Na^+ effects. The Vertisols generally tolerated exchangeable Na^+ percentages and required threshold electrolyte concentrations for maintaining adequate water transmission similar to those reported for arid temperate zone soils. It was concluded that the potential is promising for using saline waters for irrigation of selected soils in the tropics when use of such waters is necessary for expanding available water resources.

LITERATURE CITED

Andrews, L. A. and W. M. Broadfoot. 1958. The San Dimas core sampler. Soil Sci. 85:297-301.

Babcock, K. L. 1963. Theory of the chemical properties of soil colloidal systems at equilibrium. Hilgardia 34(11):417-542.

Bakker, A. C.,and W. W. Emerson. 1973. The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. III. The permeability of Shepparton soil and comparison of methods. Aust. J. Soil Res. 11:159-165.

Bower, C. A. 1959. Cation exchange equilibria in soils affected by sodium salts. Soil Sci. 88:32-35.

El-Swaify, S. A. 1970. The stability of soil aggregates in certain tropical soils as affected by solution composition. Soil Sci. 109:197-202.

El-Swaify, S. A., and W. W. Emerson. 1975. Changes in the physical properties of soil clays due to precipitated aluminum and iron hydroxides. 1. Swelling and aggregate stability after drying. Soil Sci. Soc. Amer. Proc. 39:1056-1063.

El-Swaify, S. A. and L. D. Swindale. 1968. Hydraulic conductivity of some tropical soils as a guide to irrigation water quality. Trans. 9th Intern. Cong. Soil Sci. 9:381-389.

El-Swaify, S. A. and L. D. Swindale. 1970. Effects of saline water on the chemical properties of some tropical soils. Soil Sci. Soc. Amer. Proc. 34:207-211.

McNeal, B. L. 1974. Soil salts and their effects on water movement. In Jan van Schilfgaarde, ed., Drainage for Agriculture, ASA Monograph No. 17:409-431.

McNeal, B. L. and N. T. Coleman. 1966. Effects of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Amer. Proc. 30:308-312.

Quirk, J. P. 1971. Chemistry of saline soils and their physical properties. In T. Talsma and J. R. Philip, eds., Salinity and Water Use, Wiley-Interscience:79-91.

Quirk, J. P. and R. K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci. 6:163-178.

Rhoades, J. D. 1974. Drainage for salinity control. In Jan van Schilfgaarde, ed., In Drainage for Agriculture, ASA Monograph No. 17:433-461.

Sinanuwong, S. and S. A. El-Swaify. 1974. Predicting exchangeable sodium ratios on irrigated tropical Vertisols. Soil Sci. Soc. Amer. Proc. 38:732-737.

Soil Survey Staff. 1975. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA Agric. Handbook No. 436, U. S. Govt. Printing Office, Washington, D. C.

U. S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. USDA Agric. Handbook No. 60.

FIELD TESTING OF A NEW SYSTEM FOR QUALIFYING IRRIGATION WATER

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INTRODUCTION

Prediction of the possibilities of salt accumulation, as well as the change in the composition of dissolved and exchangeable ions after irrigation is introduced in a particular area, is very important for planification and prevention purposes. The factors involved are the content and composition of the different ions in the irrigation water, and the leaching conditions. These are determined by the drainage conditions of the soil, the irrigation management, and the climate.

Many approaches have been developed to predict soil salinity changes (U.S. Salinity Lab. Staff, 1954; Doneen, 1954; Eaton, 1966). The most widely used are based on the salt balance equation which states that the amount of salt accumulating in the soil represents the difference between the amount in the irrigation water and the drainage water. Initially this approach was used only for predicting salt accumulation irrespective of ionic composition. Introducing the use of leaching efficiency factors (Dieleman, ed., 1963), soil characteristics (Bernstein, 1967), and empirical indices to predict carbonate precipitation (Bower and Maasland, 1963; Bower et al., 1968) have been proposed to improve the salt balance equation. Some approaches to predict the sodium adsorption ratio (SAR) (Pla, 1967, 1968) and exchangeable sodium percentage (ESP) (Rhoades, 1968, 1972) to be reached in the soil according to the leaching fraction have recently been developed.

A non-empirical system to predict the salt and sodium accumulation in the soil, recently developed by Pla and Dappo (1974), is evaluated in this paper, using five different situations of salt affected soils in irrigated areas of Venezuela.

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THEORY

The proposed system is based on theoretical approaches confirmed by experimental results presented in previous papers by Pla (1967, 1968). It is based on an independent balance of the more common ions in irrigation waters and in soil solution, according to the effective leaching fraction (LF) and maximum solubilities of salts under different conditions. In order to make the system appropriate for practical use some simplifications were made. Fixed values were assumed for the maximum concentrations of Ca + Mg bicarbonates and Ca sulfates in soil solution.

Maximum concentration of (Ca + Mg) bicarbonates in soil solution = 10 meq/l, when in irrigation water the concentration of Ca + Mg is equal or higher than the concentration of bicarbonates. When the concentration of bicarbonates in irrigation water is higher than the concentration of Ca + Mg, the maximum concentration of (Ca + Mg) bicarbonates in soil solution is expected to be close to the concentration of (Ca + Mg) in irrigation water. For the maximum concentration of Ca sulfate in soil solution, the value of 30 meq/l is adopted.

The use of basic infiltration as an index of the permeability of the soil profile (rapid > 5 cm/hour; medium 1-5 cm/hour; slow 0.1-1 cm/hour; very slow < 0.1 cm/hour) and of the limiting values of salt concentration (CSE) and Na (SARSE) according to the crops and soils is apparently arbitrary, but fully justified according to many evaluations reported previously (Pla and Dappo, 1974) and in this paper.

The indices used for qualifying irrigation waters are the values of effective leaching (LF) calculated with the equations of table 1 or obtained in monograms presented elsewhere (Pla and Dappo, 1974) for each set of conditions. With the values of LF, the classes of irrigation waters are found in tables 3 and 4. In those tables, the classes are based on leaching requirement values, assuming that salt and Na accumulation within the root zone can be controlled by application of extra water for leaching, but within limits determined by difficulties derived from slow percolation rates, high water tables, and drainage requirements. The maximum values of CSE and SARSE are presented as guidelines for selecting crops, soils and management practices to prevent potential problems of salinity and permeability. Such guidelines may be easily modified when warranted by local experience and information on crops and soils. The division into excellent, good, poor, and very poor quality classes is arbitrary, but supported by many observations and experimental data.

TABLE 1.- Formulas for calculating L(C)F and L(NA)F for each set of conditions.

CONDITIONS	L(C)F	L(NA)F
$BR \leq CAR$ $BR \leq 10 \times LF$ $CASR \leq 30 \times LF$	$(NAR + CAR)/CSE$	$2 \times NAR^2/SARSE^2 \times CAR$
$BR \leq CAR$ $BR > 10 \times LF$ $CASR \leq 30 \times LF$	$(NAR + CAR - BR)/(CSE - 10)$	$\frac{[SARSE^2 \times (CASR+CACLR)^2 + 80 NAR^2]^{1/2}}{20\ SARSE} - \frac{(CASR+CACLR)}{20}$
$BR \leq CAR$ $BR \leq 10 \times LF$ $CASR > 30 \times LF$	$(NAR + CAR - CASR)/(CSE - 30)$	———
$BR \leq CAR$ $BR > 10 \times LF$ $CASR > 30 \times LF$	$(NAR + CAR - BR - CASR)/(CSE - 40)$	$\frac{(SARSE^2 \times CACLR^2 + 320 \times NAR^2)^{1/2}}{80 \times SARSE} - \frac{CACLR}{80}$
$BR > CAR$	$NAR/(CSE - CAR)$	$NAR/SARSE \times (CAR/2)^{1/2}$

B: Bicarbonates; S: Sulfates; CL: Chlorides; CA: Ca+Mg; NA: Na; C: Salt Concentration; SAR: Sodium Adsorption Ratio; SE: Saturation Extract; R: Irrigation Water; L: Leaching Requirement; F: Leaching Efficiency.

TABLE 2. Climatic conditions, basic infiltration and salinity data of soils and irrigation waters in the five sites selected for the evaluation (**R:** Rainfall; E: Evaporation; SAR: Sodium adsorption ratio; LF: leaching fraction x leaching efficiency calculated for chlorides (Cl) and total salts (C) in soils and waters; B. Inf.: Basic infiltration).

SITE (Crop)	May-Oct. R (mm)	May-Oct. E	Nov-April R (mm)	Nov-April E		HCO_3^-	$SO_4^=$ (meq./l. solution)	Cl^-	Ca^{++} + Mg^{++}	Na^+	SAR	Precipitated $CO_3^=$ meq./100 g.	Precipitated $SO_4^=$	LF Cl	LF C	B.Inf. cm/hour
PARAGUANA (Melon)	190	1140	125	1000	IRR. WATER**	8	4	37	22	27	8.1					
					Soil (0-60 cm)**	3	8	54	33	29	7.1	*		0.68	0.75	20
EL CENIZO (Cotton)	620	860	490	870	IRR. WATER**	4.7	6.2	1	8.5	3.4	1.6					
					Soil (0-60 cm)**	4	122	56	75	115	19	7.2	8.0	0.02	0.02	0.3
QUIBOR (Sugar-Cane)	320	730	140	880	IRR. WATER**	3	14	1	16	2	0.7					
					Soil (0-60 cm.)**	2	40	4	36	10	2.4	6.0	3.5	0.25	0.33	0.7
YARITAGUA (Sugar-Cane)	740	540	130	780	IRR. WATER**	6	15	5	17	9	3.1					
					Soil (0-60 cm)**	3	54	24	36	45	11	4.6	2.7	0.21	0.22	0.6
LA MORITA (Citrus)	805	502	109	780	IRR. WATER**	4	0.5	1.2	3.7	2.5	1.8					
					Soil (0-60 cm)**	10	32	16	6	52	30	37		0.07	0.05	0.2

* Traces

** Saturation extract.

TABLE 3

CLASSIFICATION OF IRRIGATION WATERS ACCORDING TO LIMITING VALUES OF SALT (C) ACCUMULATION IN THE SOIL SOLUTION.

SOIL PERMEABILITY (OR DRAINAGE CONDITIONS)	CROP (CSE MAXIMUM)	L (C) F						
		<0,01	0,01-0,02	0,02-0,05	0,05-0,10	0,10-0,20	0,20-0,30	> 0,30
RAPID (WELL DRAINED)	SENSITIVE (40meq/l)	C_{11}	C_{11}	C_{11}	C_{11}	C_{21}	C_{31}	C_{41}
	TOLERANT (80meq/l)	C_{12}	C_{12}	C_{12}	C_{12}	C_{22}	C_{32}	C_{42}
	VERY TOLERANT (160meq/l)	C_{13}	C_{13}	C_{13}	C_{13}	C_{23}	C_{33}	C_{43}
MEDIUM (MODERATELY DRAINED)	SENSITIVE (40 meq/l)	C_{11}	C_{11}	C_{11}	C_{21}	C_{31}	C_{41}	C_{41}
	TOLERANT (80 meq/l)	C_{12}	C_{12}	C_{12}	C_{22}	C_{32}	C_{42}	C_{42}
	VERY TOLERANT (160 meq/l)	C_{13}	C_{13}	C_{13}	C_{23}	C_{33}	C_{43}	C_{43}
SLOW (POORLY DRAINED)	SENSITIVE (40 meq/l)	C_{11}	C_{11}	C_{21}	C_{31}	C_{41}	C_{41}	C_{41}
	TOLERANT (80 meq/l)	C_{12}	C_{12}	C_{22}	C_{32}	C_{42}	C_{42}	C_{42}
	VERY TOLERANT (160meq/l)	C_{13}	C_{13}	C_{23}	C_{33}	C_{43}	C_{43}	C_{43}
VERY SLOW (VERY POORLY DRAINED)	SENSITIVE (40 meq/l)	C_{11}	C_{21}	C_{31}	C_{41}	C_{41}	C_{41}	C_{41}
	TOLERANT (80 meq/l)	C_{12}	C_{22}	C_{32}	C_{42}	C_{42}	C_{42}	C_{42}
	VERY TOLERANT (160 meq/l)	C_{13}	C_{23}	C_{33}	C_{43}	C_{43}	C_{43}	C_{43}

L = LEACHING REQUIRED; **C** = TOTAL SALTS IN THE SOIL SOLUTION; **F** = LEACHING EFFICIENCY;

CSE = SALT CONCENTRATION IN THE SATURATION EXTRACT.

FIRST SUBINDEX:
(1) EXCELENT WATER QUALITY.
(2) GOOD WATER QUALITY.
(3) POOR WATER QUALITY.
(4) VERY POOR WATER QUALITY.

SECOND SUBINDEX:
(1) SENSITIVE CROP.
(2) TOLERANT CROP.
(3) VERY TOLERANT CROP.

TABLE 4

CLASSIFICATION OF IRRIGATION WATERS ACCORDING TO SODIUM (NA) ACCUMULATION IN THE SOIL

SOIL PERMEABILITY	MAXIMUM SARSE	L (NA) F						
		< 0,01	0,01-0,02	0,02-0,05	0,05-0,10	0,10-0,20	0,20-0,30	> 0,30
RAPID	15	NA_{11}	NA_{11}	NA_{11}	NA_{11}	NA_{21}	NA_{31}	NA_{41}
	20	NA_{12}	NA_{12}	NA_{12}	NA_{12}	NA_{22}	NA_{32}	NA_{42}
	30	NA_{13}	NA_{13}	NA_{13}	NA_{13}	NA_{23}	NA_{33}	NA_{43}
MEDIUM	10	NA_{11}	NA_{11}	NA_{11}	NA_{21}	NA_{31}	NA_{41}	NA_{41}
	15	NA_{12}	NA_{12}	NA_{12}	NA_{22}	NA_{32}	NA_{42}	NA_{42}
	20	NA_{13}	NA_{13}	NA_{13}	NA_{23}	NA_{33}	NA_{43}	NA_{43}
SLOW	5	NA_{11}	NA_{11}	NA_{21}	NA_{31}	NA_{41}	NA_{41}	NA_{41}
	10	NA_{12}	NA_{12}	NA_{22}	NA_{32}	NA_{42}	NA_{42}	NA_{42}
	15	NA_{13}	NA_{13}	NA_{23}	NA_{33}	NA_{43}	NA_{43}	NA_{43}
VERY SLOW	5	NA_{11}	NA_{21}	NA_{31}	NA_{41}	NA_{41}	NA_{41}	NA_{41}
	10	NA_{12}	NA_{22}	NA_{32}	NA_{42}	NA_{42}	NA_{42}	NA_{42}
	15	NA_{13}	NA_{23}	NA_{33}	NA_{43}	NA_{43}	NA_{43}	NA_{43}

L: LEACHING REQUIRED; NA: SODIUM; F: LEACHING EFFICIENCY

SARSE: SODIUM ADSORPTION RATIO IN THE SATURATION EXTRACT

FIRST SUBINDEX
(1)EXCELENT WATER QUALITY
(2)GOOD WATER QUALITY
(3)POOR WATER QUALITY
(4)VERY POOR WATER QUALITY

SECOND SUBINDEX
(1) LOW SARSE
(2) MEDIUM SARSE
(3) HIGH SARSE

MATERIALS

Five profiles of salt affected soils (Figure 1) in irrigated areas of Venezuela, representing a wide range of conditions in relation to climate, soil properties, and composition of irrigation waters (Table 2) were selected for the present evaluation. Rainfall and evaporation are presented for the two seasons generally distinguished in the tropical areas of the northern hemisphere. Only in two cases (Yaritagua and La Morita) an excess of rainfall over evaporation is observed in the rainy season. Basic infiltration values show that in four of the soils the percolation rates are rather low, Paraguana being the exception. Salt content in irrigation waters ranges from very high in Paraguana to low in La Morita, with very different relative concentrations of the different cations and anions. Based on the time they have been under irrigation, and continuity of cropping practices, it is assumed that conditions close to equilibrium have been reached in all cases. In table 2, salinity and SAR values are reported as an average for the 0-60 cm. depth section, assuming that local and seasonal variations due to different climatic and cropping factors occur withing that depth. According to the characteristics of rainfall and soils, the leaching effects of the excess of precipitation over evaporation in Yaritagua and La Morita is considered to be negligible, as it was shown by Pla (1972).

RESULTS AND DISCUSSION

The LF values in table 2 were calculated from equations in table 1. The actual concentration of the different ions in water and in soil solution (saturation extract 0-60 cm) was calculated using as a reference in one case (Cl) as the concentration of the non precipitating anion Cl^-, and in the other (C) as the different ions altogether. A very good agreement between both LF values demonstrates that the provisions taken for salt precipitation in the calculation of LF using equations of table 1, are very precise for all cases. A further confirmation of the validity of the equations is shown by the very good correspondence among the LF values of table 2 and the LF values in table 5 calculated for CSE similar to the actual values reached in each soil. Table 5 presents the LF values calculated for different limiting values of CSE and SARSE, as well as the predicted possibilities of precipitation of (Ca + Mg) carbonates ($CO_3^=$) and Ca sulfates ($SO_4^=$). The classes of the different irrigation waters according to tables 3 and 4 is also shown in table 5. The prediction of precipitation of carbonates and sulfates in the soil agree very well with the actual data in table 2, for similar values of LF.

The validity of the system for predicting Na accumulation under field conditions may be evaluated comparing the actual LF and SAR values in saturation extracts of table 2, with the calculated LF for similar SARSE values in table 5. The agreement among them is very good.

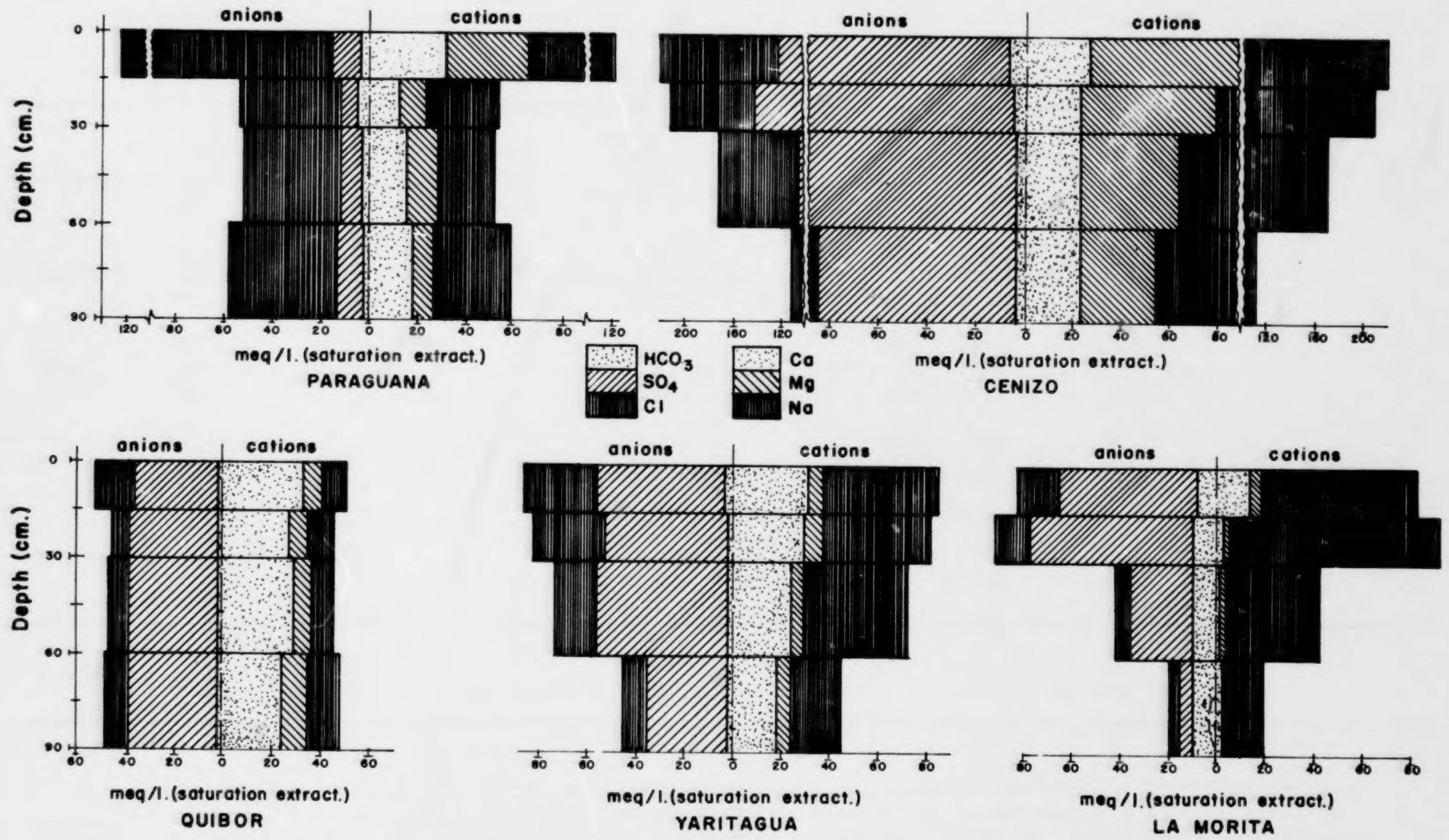

Figure 1.— Distribution with depth of the soluble salts in the five selected soil profiles.

TABLE 5. Calculated leaching (LF: leaching fraction x leaching efficiency), predicted precipitation of carbonates ($CO_3^=$) and sulfates ($SO_4^=$), and classification of the irrigation waters according to maximum values of salt concentration (C) and sodium adsorption ratio (SAR) in the saturation extract (SE). (See tables 3 and 4).

IRRIGATION WATER		MAXIMUM C (SE) meq./1.			MAXIMUM SAR (SE)				
		40	80	160	5	10	15	20	30
PARAGUANA	LF		0.59	0.27		0.70	0.37	0.22	0.10
	PREDIC. PRECIP.		$CO_3^=$	$CO_3^=$		$CO3^=$	$CO_3^=$	$CO_3^=$	$CO_3^=$
	CLASS.	C41	C42	C33			NA41	NA32	NA13
EL CENIZO	LF	0.24	0.09	0.03	0.17	0.08	0.05	0.04	
	PREDIC. PRECIP.	$CO_3^=$-	$CO_3^=$ $SO_4^=$	$CO_3^=$ $SO_4^=$	$CO_3^=$	$CO_3^=$ $SO_4^=$	$CO_3^=$ $SO_4^=$	$CO_3^=$ $SO_4^=$	
	CLASS.	C41	C32	C23	NA41	NA32	NA23		
QUIBOR	LF	0.45	0.05	0.02	0.09	0.04	0.03		
	PREDIC. PRECIP.		$CO_3^=$ $SO_4^=$	$CO_3^=$ $SO_4^=$	$CO_3^=$ $SO_4^=$	$CO_3^=$ $SO4^=$	$CO_3^=$ $SO_4^=$		
	CLASS.	C41	C22	C13	NA31	NA22	NA23		
YARITAGUA	LF	0.65	0.22	0.08	0.42	0.20	0.13		
	PREDIC. PRECIP.		$CO_3^=$ $SO_4^=$	$CO_3^=$ $SO_4^=$	$CO_3^=$	$CO_3^=$ $SO_4^=$	$CO_3^=$ $SO_4^=$		
	CLASS.	C41	C42	C33	NA41	NA41	NA43		
LA MORITA	LF	0.07	0.03	0.02	0.37	0.18	0.12	0.09	0.06
	PREDIC. PRECIP.	$CO_3^=$	$CO_3^=$	$CO_3^=$	$CO_3^=$	$CO_3^=$	$CO_3^=$	$CO_3^=$	$CO_3^=$
	CLASS.	C31	C22	C13	NA41	NA42	NA43		

Classification of irrigation waters for different CSE and SARSE values, reported in table 5, show that in Paraguana high leaching is required for salinity control, even with tolerant crops, and that the salinity problem, not the permeability problem, is the critical one. In El Cenizo, Quibor, and Yaritagua, high leaching would be required for sensitive crops, but due to the enhanced precipitation of carbonates and particularly Ca sulfate, such leaching requirements suffer a very drastic reduction when values of CSE for tolerant crops are set as the limiting ones. Salinity problems are dominent over Na-permeability problems in El Cenizo and Quibor, while in Yaritagua, at low LF values, the Na-permeability problem may be the limiting one. The classification of La Morita irrigation water shows a potential Na-permeability problem dominating in any case over salinity problems. Actual diagnosis of the different problems in the field, and evaluations through field and laboratory leaching trials (not reported in this paper), agree very well with the previous conclusions.

According to the evidence presented here, where five salt-affected soils, selected from many samples, have been used to illustrate the validity of the proposed approach, it is concluded that this system may be used in estimating the potential hazards of salinity and sodium to crops and soils associated with long term use of a particular water under very different conditions, and in selecting the best management alternatives to prevent such hazards. Following the same approach, the gypsum requirement of the irrigation water to reduce, if necessary, the leaching requirement for controlling SARSE may be calculated (Pla, 1969).

Compared with this system, other approaches recently proposed for the same purpose are mostly empiricial, lacking the required flexibility to be usable under different conditions from those where they were developed.

SUMMARY

A new system for evaluating irrigation waters in relation to the potential problems of salinity and sodicity is tested under five different situations of salt affected soils in Venezuela. The system is based on an independent balance of the different ions in soil solution in relation to the effective leaching and limiting solubilities of Ca sulfates and Ca plus Mg carbonates. Qualification is based not only on the concentration and composition of salts in irrigation water but on the drainage conditions of the soil profile and on the crop tolerance. Some simplifications are introduced to facilitate the practical use of the system. No empirical indices are required. The selected soils and waters cover a wide range of salt and sodium problems as well as different climatic conditions. The test is based on a comparison among measured

and predicted values of total and individual salt concentrations and ionic composition both in solution and precipitated, as well as in the correspondence among observed and predicted properties of the affected soils. Very good agreement for all sets of conditions shows that the proposed system may be of universal application and very useful for predicting the kind and degree of salinity problems to be developed in irrigated soils and to suggest the best alternatives for the use and management of a particular irrigation water.

REFERENCES

Bernstein, L. 1967. Quantitative assessment of irrigation water quality. Amer. Soc. Testing and Materials Spec. Tech. Publ. 416: 51-65.

Bower, C.A. and M. Maasland. 1963. Sodium hazard of Punjab ground waters. Proc. Symp. Waterlogging and Salinity in West Pakistan. 49-61.

Bower, C.A., G. Ogata, and J.M. Tucker. 1968. Sodium hazard of irrigation waters as influenced by leaching fraction and by precipitation of calcium carbonate. Soil Sci. 106: 29-34.

Dieleman, P.J. (Ed.). 1963. Reclamation of salt affected soils in Iraq. Int. Inst. Land Reclamation and Improvement. Publ. 11. Wageningen. The Netherlands.

Doneen, L.D. 1954. Salination of soil by salts in the irrigation water. Trans. Amer. Geophys. Union 35: 943-950.

Eaton, F.M. 1966. Total salt and water quality appraisal. In Diagnostic criteria for plants and soils. Univ. of Calif. Davis. Agric. Sci. 501-509.

Pla, I. 1967. Evaluación cualitativa de los efectos de los bicarbonatos en el agua de riego sobre las propiedades químicas y físicas de los suelos y factores que influyen sobre la magnitud de tales efectos. Revista Facultad de Agronomía. Alcance 12. Maracay. Venezuela.

Pla, I. 1968. Evaluation of the quality of irrigation waters with high bicarbonate content in relation to drainage conditions. Trans. 9th Int. Congr. Soil Sci. 1: 357-370.

Pla, I. 1969. Calcium required as an amendment for irrigation waters with high bicarbonate content in relation to the drainage conditions. Agrokemia és Talajtan. Supplementum. 18: 283-289. Budapest. Hungary.

Pla, I. 1972. Salt and water balances in irrigated soils under tropical conditions. In Proceedings of the symposium on new developments in in the field of salt-affected soils. (In press). Cairo. Egypt.

Pla, I. and F. Dappo. 1974. Sistema racional para la evaluación de calidad de aguas para riego. Suplemento Técnico n° 12. FUDECO. Barquisimeto. Venezuela.

Rhoades, J.D. 1968. Leaching requirement for exchangeable sodium control. Soil Sci. Soc. Am. Proc. 32: 652-656.

Rhoades, J.D. 1972. Quality of water for irrigation. Soil Sci. 113: 277-284.

U.S. Salinity Lab. Staff. 1954. Diagnosis and improvement of saline and alkali soils. USDA Handbook n° 60. Washington, D.C.

SALINITY SURVEY IN ISRAEL [1]

M. Boaz, I. Husenberg and Y. Posin [2]

GENERAL

The Salinity Survey was initiated in the spring of 1963, a year before the operation of the National Water Carrier. The National Water Carrier conducts water from Lake Tiberias, in the north, to the southern parts of the country (Fig. 1).

The electrical conductivity (EC) of the lake water at that time was about 1.5 millimhos/cm, with a chloride content of about 350 p.p.m. and about 1000 p.p.m. total dissolved salts (TDS). (The salinity of the lake water at the present time is considerably lower: EC 1.2 mmhos/cm.; Cl 250 p.p.m.; TDS 840 p.p.m.). It was feared that the water would be too saline for the irrigation of sensitive crops like citrus, which is Israel's main agricultural export.

The Salinity Survey (Fig. 2) is a perennial follow-up of the effects of water salinity on:

- Soil salinity
- The accumulation and leaching of salts in different soils and regions
- Crops and yields, mainly on citrus.

Table 1. Division of Salinity Survey plots according to crops

Crop / Yr	Citrus	Deciduous	Avocado	Vineyards	Field Crops	Non-Irrigated	Total No. of Plots
1963	84	13	-	16	25	7	148
1966	187	56	12	27	51	28	361
1968	184	56	29	23	111	22	325
1969	180	47	38	15	11	19	310
1971	187	22	36	-	8	-	253
1973	122	9	131	-	14	-	276

Over the years, the number of plots was decreased considerably in deciduous orchards and field crops and was increased in avocado (Table 1), which is considered sensitive to salinity and is in constant expansion for export.

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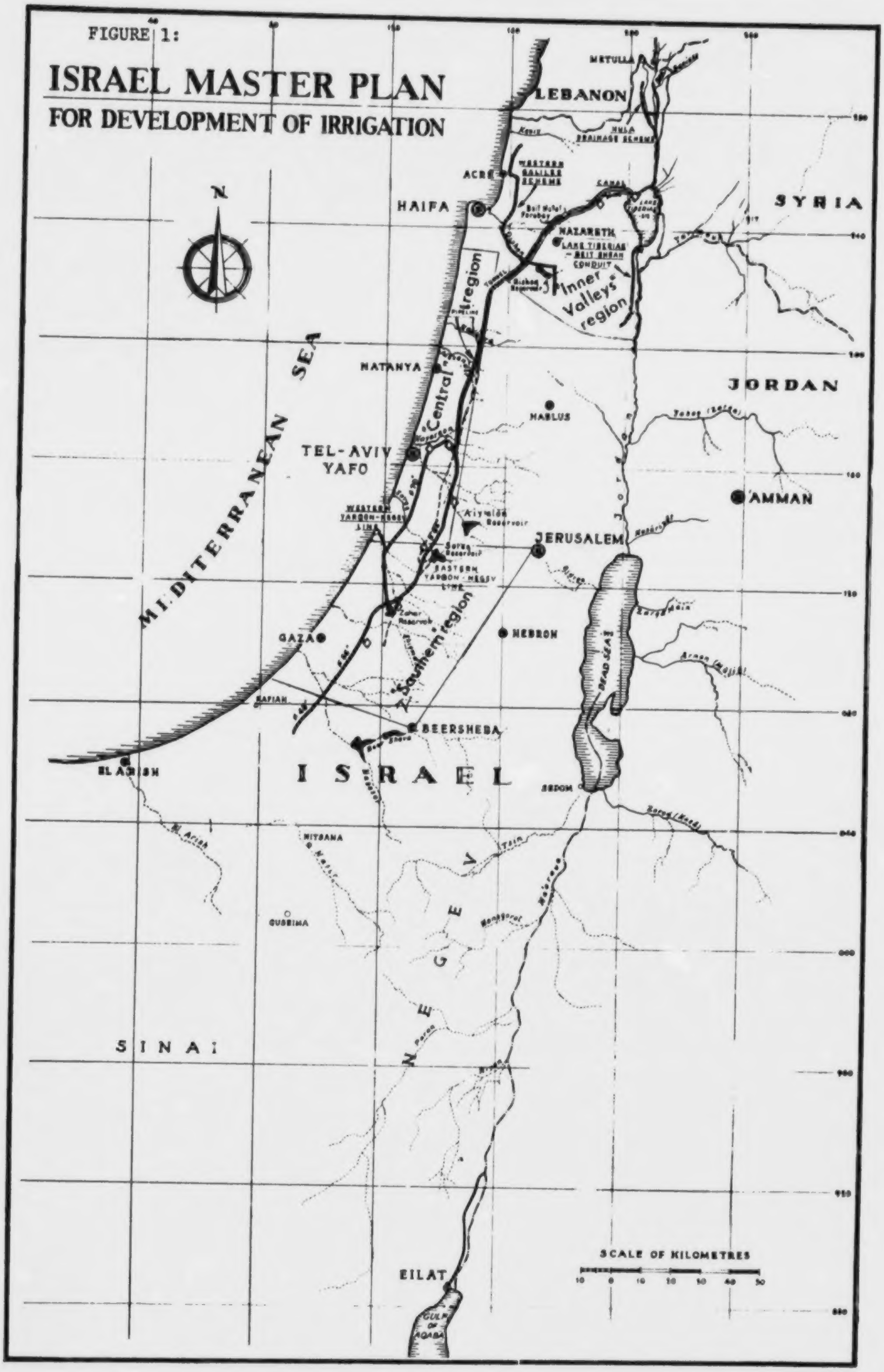
[1] The salinity survey is being carried out by a team of the Irrigation and Soil Field Service, Extension Services, Ministry of Agriculture.

[2] Irrigation and Soil Field Service, Ministry of Agriculture, Tel-Aviv, Israel.

FIGURE 1:

ISRAEL MASTER PLAN FOR DEVELOPMENT OF IRRIGATION


N
METULLA
LEBANON
HULA DRAINAGE SCHEME
WESTERN GALILEE SCHEME
ACRE
CANAL
HAIFA
SYRIA
Beit Netofa Forebay
NAZARETH
LAKE TIBERIAS - BEIT SHEAN CONDUIT
Tunnel
"Inner Valleys" region
region
Pipeline
MEDITERRANEAN SEA
NATANYA
JORDAN
"Central" region
NABLUS
TEL-AVIV YAFO
AMMAN
WESTERN YARQON-NEGEV LINE
Aiyalon Reservoir
JERUSALEM
Sorek Reservoir
EASTERN YARQON-NEGEV LINE
Zohar Reservoir
GAZA
HEBRON
"Southern" region
DEAD SEA
RAFIAH
BEERSHEBA
EL ARISH
ISRAEL
SEDOM
NITSANA
NEGEV
QUSEIMA
SINAI
EILAT
GULF OF AQABA
SCALE OF KILOMETRES
10 0 10 20 30 40 50

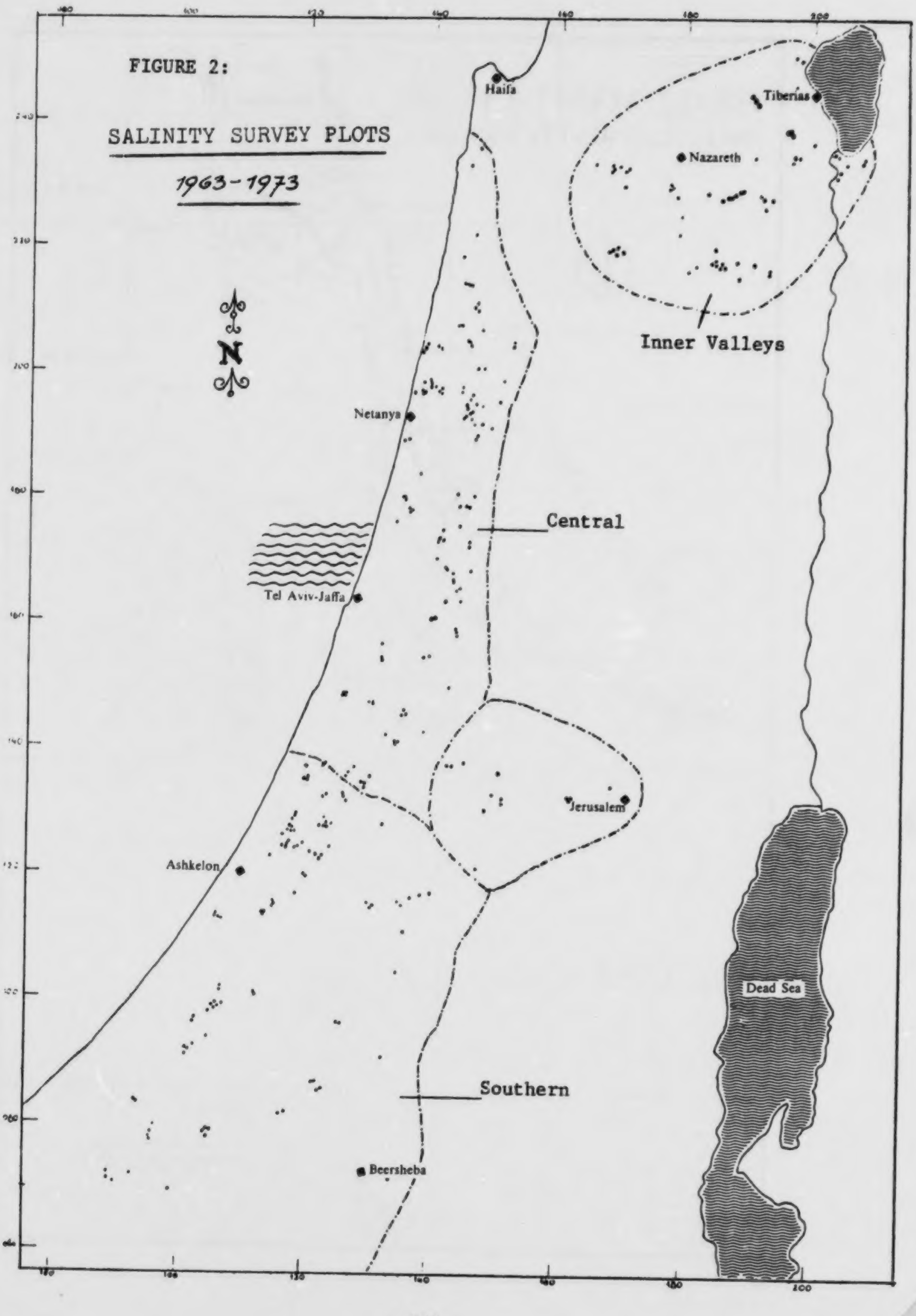


FIGURE 2:

SALINITY SURVEY PLOTS

1963-1973

N
Haifa
Tiberias
Nazareth
Inner Valleys
Netanya
Central
Tel Aviv-Jaffa
Jerusalem
Ashkelon
Southern
Beersheba
Dead Sea

Collection of Data

The data collected in the survey include:

- Soil salinity EC, Cl, Na, Ca+Mg in the spring (after the rainy season) and in the fall (after the irrigation season), to a depth of 150 cm. at 30 cm. layers (5 depths x 4 rep.).

  The soil salinity is tested in the extract of the saturated soil paste and the saturation percentage (SP) is used also as a soil type characteristic.

- Salinity of the irrigation water, 4 times per season.
- Annual rainfall

Additional data are collected in the citrus and avocado plots.

- Yields from marked trees on 1 dunam area (0.1 hectare), including total yield and grade.
- Leaf analyses, include Cl, Na, Ca, Mg, N, P, and K.
- Evaluation of crop growth, in relation to agrotechnical treatments and general impression of the plot.
- The cation exchange capacity (CEC) and the exchangeable sodium percentage (ESP) of the soils in all citrus plots were tested once, in the fall of 1968.
- The boron (B) was tested once in the fall of 1968: in the irrigation water for all plots and in the soil and leaves in the citrus plots.

Up to the spring of 1973 a total of about 900,000 data items have been collected in the survey. The data processing and computations include tabulation and statistical analyses by computer.

Seasonal and annual tabulations are being issued according to subject matter and plots. An example of such a tabulation in the form of an annual plot report is illustrated in Table 2.

Table 2. Salinity Survey. Annual Plot Report

A. Site Conditions

Year: 1968
Plot No. 73
Region: Negev
Settlement: Saad

Coordinates: 10680 x 09890
Crop : Citrus
Variety : Valencia
Stock : Sour orange

Planting: 1958
Water: National Water Carrier
Rainfall: 1967/68: 453 mm.
Irrig. method: Under-tree sprinkler

B. Soil Salinity

Lay cm.	SP %	EC mmho/cm	Cl meq/1	Na meq/1	Ca+Mg meq/1	B p.p.m.	SAR	ESP %
S P R I N G								
0- 30	54.00	0.86	0.92	4.17	4.90		2.91	
30- 60	55.00	0.74	1.35	6.01	1.54		7.50	
60- 90	56.00	0.90	1.74	7.03	2.07		9.52	
90-120	56.00	1.49	3.13	9.03	7.25		5.24	
120-150	56.00	1.54	5.23	6.63	9.46		3.05	
0- 60	54.50	0.80	1.14	5.09	3.22		5.21	
0- 90	55.00	0.83	1.34	5.73	2.83		6.31	
0-120	55.25	1.00	1.78	6.56	3.94		6.04	
0-150	55.40	1.11	2.47	6.58	5.04		5.44	
F A L L								
0- 30	54.00	1.07	4.85	4.95	5.51	0.30	2.98	8.1
30- 60	55.00	1.22	5.48	7.41	4.60	0.28	4.91	11.7
60- 90	56.00	1.27	5.42	8.43	3.78	0.02	6.15	11.7
90-120	56.00	1.42	5.95	8.53	4.94	0.02	5.42	10.5
120-150	56.00	1.56	5.39	7.19	8.55	0.02	3.54	11.1
0- 60	54.50	1.15	5.16	6.18	5.05		3.94	
0- 90	55.00	1.19	5.25	6.93	4.63		4.68	
0-120	55.25	1.24	5.42	7.33	4.71		4.86	
0-150	55.40	1.31	5.42	7.30	5.47		4.60	

C. Water Salinity (seasonal average) and Application

EC	Cl	SO_4	CO_3+ HCO_3	NO_3	Na	Ca+Mg	K	TDS	SAR	B	Water Appl.	
mmhos/cm	milliquivalents/ liter							p. p.m		p.p.m	mm.	no.
1.30	8.16	1.76	5.00		10.00	4.80	0.12	900	6.45	0.11	735	8

D. Leaf Analysis

Cl	Na	Mg	Ca	N	P	K	B
% of dry matter							p. p. m
0.27	0.14	0.39	5.90	2.15	0.12	0.35	93.80

E. Yield

Date of picking	No. of trees	Area picked,	Wt. of picked fruit	"Brara" (low-grade)	Gross yield	Yield per tree
		dunam	ton	%	ton/d	kg
April 69	56	1.0	4.0	32.5	4.0	71

Statistical Analyses

In order to find correlations between the different salinity constituents, and between the yield, the salinity, and other factors, simple and multiple linear regressions were computed by a computer program of stepwise regression . This program computes a sequence of multiple linear regression equations in a stepwise manner. At each step, the variable which has the highest partial correlation with the dependent variable is added to the regression equation. The various regressions include quantitative variables such as Cl, Na, Sp,etc., as well as qualitative variables, expressed as "dummy-variables", such as Region, Period of planting,etc., and simple interactions between any two variables.

In each case the regression equation, the coefficient of determination (R^2), and the number of observations (n), are given.

The coefficient of determination indicates the percent of variation which is explained by the variables in the regression.

Following is an example of a typical regression.

The variables which entered the regression are:

$Y =$ Yield - tons per dunam
Citrus - Shamuti and Valencia x sour orange

$X_1 =$ Cl in the irrigation water - meq/litre

$X_2 =$ SP - average in the soil profile, 0-90 cm. - %

$X_3 =$ Cl in water x SP. Interaction between two quantitative variables.

$X_4 =$ Cl in water x Region - 2 regions
Interaction between a quantitative variable (Cl) and a "dummy" variable (region). Central region = 1; Southern region = -1.

The resulting regression equation is:

$$Y = 11.8 - 1.48(X_1) - 0.12\,(X_2) + 0.023\,(X_3) + 0.065\,(X_4)$$

$$R^2 = 0.59 \qquad (R = 0.77) \qquad n = 58$$

The significance level of R = 0.1%.

Figure 3. Perennial Soil Salinity Fluctuations

Cl in the Spring in Citrus and other Orchard Plots
Averages for Soil Profiles 0-90 cm. and 90-150 cm.

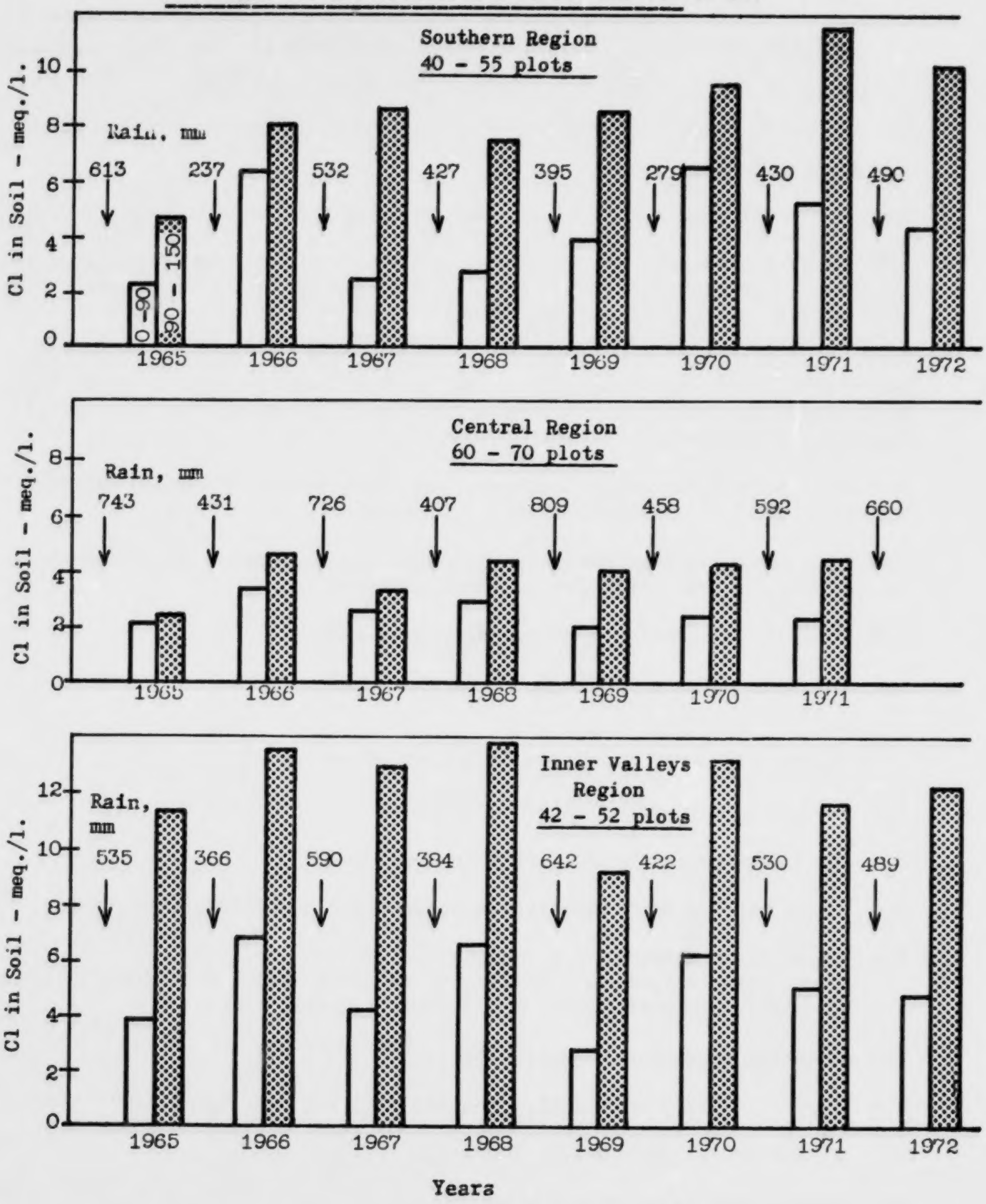


Table 3. Cl in soil in the spring as a function of Cl in soil in the fall amount of rainfall and SP.

Year	Soil Profile cm	Regression Formula	Multiple Correlation Coefficient R	No. of Plots	Amount of Rainfall Average of All Plots mm
1965	0 - 90	$Cl_S = 2.87 + 0.58\ Cl_F - 0.01r + 0.05SP$	0.811	255	339
	0 -150	$Cl_S = 1.86 + 0.68\ Cl_F - 0.01r + 0.05SP$	0.886	255	
1966	0 - 90	$Cl_S = 1.98 + 0.32\ Cl_F - 0.04r + 0.007SP$	0.691	260	617
	0 -150	$Cl_S = 1.89 + 0.52\ Cl_F - 0.006r + 0.03SP$	0.823	260	

Cl_S = Average Cl concentration in saturated soil extract in the spring - meq/1.

Cl_F = As above - in the Fall

r = Average annual rainfall

SP = Saturation Percentage

Table 4. Relation and correlation between Na and Cl in the irrigation water in different regions

Region	n	Na	Cl	$\frac{Na}{Cl}$ x100%	r between Na and Cl
		Meq./1.			
Inner Valleys	37	5.05	6.90	73	0.90
Central	77	4.29	5.97	72	0.85
Valleys+ Center	114	4.52	6.25	72	0.86
Southern	55	6.67	7.54	88	0.65

MAIN FINDINGS

Soil salinity levels and correlations between salinity constituents

Due to efficient water use in most parts of the country, accumulation of dissolved salts takes place in the soil profile of the main rootzone, from spring to fall. It is possible to forecast the average soil salinity in the fall on the basis of the average soil salinity in the spring and the salinity of the irrigation water (Fig. 3, Table 3).

For citrus plantations on light soils in the Central region, it was found that the soil salinity in the fall is a function of the salinity in the irrigation water only, since there is a full leaching of salts from the rootzone nearly every winter in that region. The ratio between the Cl content in the soil in the fall (meq/l in saturation extract) to Cl content in the irrigation water (in meq/l), was found to be approximately 1:1, in citrus plantations on light soils in the Central region.

In the Southern region there is a certain accumulation of salts in the soil as a result of low rainfall and efficient water use. The Na level in the soil in the spring is usually higher than the Cl level, due to hydrolysis and exchange processes following the winter.

In the Inner Valleys region the soils are heavy and salt leaching from the main rootzone is not full, depending on the amount and distribution of rainfall. In the following diagram, the average values of Cl (Fig. 1) in the soil in the spring for the years 1965-1972 are given.

The values are averages for the soil profile (0-90 cm), from all citrus and other orchard plantations in the survey, in three different regions.

The correlation between the exchangeable sodium percentage (ESP) and the sodium adsorption ratio (SAR) in the saturated soil extract, was computed from 776 soil samples of different soil types. It was found that the heavier the soil (higher SP), the better is the correlation. Good correlation was obtained for soils of SP 80%. Very poor correlation was obtained in light and medium light soils with SP 60%. Very good correlations were obtained between some salinity constituents in the irrigation water:

- Between total dissolved salts (TDS) and the electrical conductivity (EC)
- Between EC and Cl content in the water
- Between EC and Na content in the water

According to these relationships we find, for example, that irrigation water with EC of 1 mmho/cm. will contain on the average:

725 ppm total dissolved salts, 180 ppm Cl, which comprise about 25% of the total dissolved salts, and 85 ppm Na, which comprise about 12% of the total dissolved salts.

The higher the total salinity, the higher the % of Cl and % of Na, in relation to the total salts in the water (Table 4).

Correlation between salinity and other factors, and citrus yields

The citrus plots in the survey include 4 combinations of variety x rootstocks: Shamuti x sweet lime; Shamuti x sour orange; Valencia x sour orange and grapefruit x sour orange.

All Shamuti and Valencia plots are within the Central and Southern regions, and most of the grapefruit plots are in the "Inner Valleys" region.

The range of Cl content in the irrigation water for all citrus plots in the survey, is about 70-425 p.p.m.

The Shamuti and Valencia plots on the sour orange rootstock were combined in the correlation analysis, since they are similar in respect to their irrigation water salinity and soil types, and also in their yield response to those factors. The analyses are based on yields of 8 years (1965-1972) in most plots.

A. Shamuti x sweet lime (Sh x SL)

64 plots, 50 of which are in the Central region and 14 in the Southern region. All plots in the Southern region are irrigated with water of over 200 p.p.m. Cl, and the soil salinity in the spring in that region is relatively high. In the statistical analysis it was attempted to evaluate the effect of the different factors on the total yield.

1. Salinity of irrigation water (Sh x SL)

No effect (no significant correlation) on the yield with irrigation water containing up to 200 p.p.m. Cl (or up to 100 p.p.m. Na), was found. In plots irrigated with water containing over 200 p.p.m. Cl, an average decrease in yield of about 0.75 ton/d. for every additional 100 p.p.m. Cl in the irrigation water, was obtained in the Central region. In the Southern region, due to higher soil salinities in the spring, the rate of yield decrease was higher. The average Cl content in the irrigation water was 227 p.p.m. with a standard deviation (S.D.) of 97 p.p.m.

2. Cl content in leaves (Sh x SL)

A significant correlation was found between the yield and the Cl content in the leaves. An average decrease in yield of about 170 kg/d. was obtained for an increase of 0.1% in Cl content in the leaves. The average Cl content in the leaves was 0.5%; S.D. = 0.39%.

A significant correlation was also found between the Cl content in leaves and the Cl concentration in the irrigation water, with an interaction with the soil type.

3. SP - Saturation Percentage (Sh x SL)

A significant correlation between the yield and the soil type, expressed in terms of SP, was found. The heavier the soil (higher SP) the lower are the yields, at an average rate of about 375 kg/d for an increase of 5% in SP. The average SP to a depth of 0-90 cm. is about 33%; S.D. = 12%.

4. Exchangeable Sodium (ESP) Percentage - (Sh x SL)

A significant correlation between the yield and the ESP was found. With an increase of the ESP in the soil there is a decrease in yield at an average rate of 150-180 kg/d for an increase of 1% in ESP.

The average ESP to a depth of 0-90 cm. was 4.7%; S.D. = 4.25%.

B. Shamuti and Valencia x sour orange (Sh x Va x SO)

58 plots, 23 of which are in the Central region and 35 in the Southern region. All plots in the Southern region are irrigated with water containing over 200 p.p.m. Cl.

1. Salinity of irrigation water (Sh, Va x SO)

No effect on the yield with irrigation water containing up to 200 p.p.m. Cl (or up to 100 p.p.m. Na) was found. For plots in the Southern region, an average decrease in yield of about 400 kg/d for every additional 100 p.p.m. Cl in the irrigation water was obtained. As a result of the interaction between water salinity and soil type, a given increase in water salinity may cause a greater yield decrease in lighter soils than in heavier soils. The same effect was also found in Shamuti x sweet lime.

2. SP - Saturation Percentage (Sh, Va x SO)

The yield was found to be positively correlated with SP. The range of SP in these plots was rather narrow.

3. ESP, Cl or Na in leaves (Sh, Va x SO)

No significant correlations were found between yield and ESP nor between yield and Cl or Na in leaves.

C. Grapefruit x sour orange (Gr x SO)

54 plots, 40 of which are in the Inner Valleys region. 44 plots are irrigated with water containing over 200 p.p.m. Cl.

Most of the grapefruit plots in the survey were planted on heavy to very heavy soils.

1. Salinity of irrigation water (Gr x SO)

Of all the 4 combinations of variety x rootstock, the Gr x SO was found to be least sensitive to salinity.

2. SP - Saturation Percentage (Gr x SO)

No significant correlation was found between yield and SP. In heavy soils additional soil characteristics should be tried.

3. ESP, Cl or Na in leaves (Gr x SO)

No significant correlations were found between yield and ESP; nor between yield and Cl or Na in leaves.

PRINCIPAL FINDINGS

1. The order of susceptibility to salinity was: Shamuti x sweet lime> Shamuti x sour orange≥Valencia x sour orange>grapefruit x sour orange.

2. In the citrus orchards of Israel there was a closer correlation between salinity of irrigation water and yields than between soil salinity and yields.

3. The yields of Shamuti and Valencia oranges were not significantly affected by irrigation water containing less than 100 p.p.m. sodium and/or less than 200 p.p.m. chlorides. Grapefruit was even less affected: irrigation water containing as high as 250 p.p.m. sodium and 390 p.p.m. chlorides caused no significant reduction of yields.

4. In Shamuti x sweet lime, the use of irrigation water of higher than the above salinity results in a decrease of yield of about 1 ton per dunam for an additional 50 p.p.m. sodium and 0.75 ton per dunam for an increment of 100 p.p.m. chlorides in the irrigation water. For Shamuti and Valencia on sour orange rootstock, the yield decreases are smaller.

5. The correlation between the salinity of irrigation water and citrus yield is more significant for sodium than for any other salinity constituent in the irrigation water.

WATER QUALITY FOR AGRICULTURE

Robert S. Ayers 1/ and Dennis W. Westcot 2/

PART I. WATER QUALITY EVALUATION

INTRODUCTION

In determining water availability for irrigation, information is required on both the quantity and quality; however, the quality need has often been neglected. Quality should infer how well a water supply fulfills the needs of the intended user and must be evaluated on the basis of its suitability for the intended use.

If two different water supplies are available, one will usually produce better results or cause fewer problems than the other and is therefore considered more acceptable or of better quality. In the case of drinking water, people have always expressed a preference for one water supply over another. The better tasting one becomes the preferred water supply. This is a personal preference, but taste is a simple evaluation based on the relative acceptability for the intended use.

Specific uses will have different quality needs. For example, most river waters are of good quality for irrigation but may be unacceptable for municipal use without treatment. After chlorination, low salinity water is of excellent quality for municipal use but may be too corrosive for industrial use without further treatment. Such a low salinity water may also cause soil permeability problems in irrigated agriculture.

Experience in use will give rise to "degrees" of acceptability which allow an assessment of the suitability of various waters for a particular use. With sufficient reported experience, this knowledge can be organized into guidelines.

This procedure has been the basis for the many guidelines for irrigation water quality that have been proposed and used over the last forty years to evaluate the soil and cropping problems associated with certain constituents in the irrigation water. One set of guidelines has built upon the previous set and each new set has improved our predictive capability. A good review and evaluation of the types of guidelines previously used to evaluate water quality for agriculture is given in the FAO/UNESCO International Sourcebook on Irrigation, Drainage and Salinity (1973).

The present paper summarizes the major points included in FAO Irrigation and Drainage Paper 29 (1976).

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EFFECT ON AGRICULTURE

Water used for irrigation always contains measurable quantities of dissolved substances which, as a general collective term, are called salts. These include relatively small but important amounts of dissolved solids originating from dissolution or weathering of the rocks and soil and dissolving of lime, gypsum and other salt sources as water passes over or percolates through them.

The suitability of a water for irrigation will be determined by the amount and kind of salts present. With poor water quality, various soil and cropping problems can be expected to develop. Special management practices may then be required to maintain full crop productivity. With good quality water there should be very infrequent or no problems affecting productivity.

The problems that result from using a poor quality water will vary both as to kind and degree but the most common ones are:

1. Salinity: A salinity problem related to water quality occurs if the total quantity of salts in the irrigation water is high enough that salts accumulate in the crop root zone to the extent that yields are affected. If excessive quantities of soluble salts accumulate in the root zone, the crop has extra difficulty in extracting enough water from the salty soil solution. This reduced water uptake by the plant can result in slow or reduced growth and may also be shown by symptoms similar in appearance to those of drought such as early wilting. Some plants exhibit a bluish-green color and heavier deposits of wax on the leaves. These effects of salinity may vary with the growth stage and in some cases may go entirely unnoticed due to a uniform reduction in yield or growth across an entire field. The mechanism of water uptake has been studied extensively, and it now appears the plant takes most of its water from and responds more critically to salinity in the upper part of the root zone than to the salinity level in its lower depths when using normal irrigation practices (Bernstein and Francois, 1973). Thus, managing this critical upper root zone may be as important as providing adequate leaching to prevent salt accumulation in the total root zone.

2. Permeability: A permeability problem related to water quality occurs when the rate of water infiltration into and through the soil is reduced by the effect of specific salts or lack of salts in the water to such an extent that the crop is not adequately supplied with water and yield is reduced. The poor soil permeability makes it more difficult to supply the crop with water and may greatly add to cropping difficulties through crusting of seed beds, waterlogging of surface soil, and accompanying disease, salinity, weed, oxygen and nutritional problems. It is evaluated, firstly, from total salts in the water since low salt water can result in poor soil permeability due to the tremendous capacity of pure water to dissolve and remove

calcium and other solubles in the soil and, secondly, from a comparison of the relative content of sodium to calcium and magnesium in the water. Furthermore, carbonates and bicarbonates can also affect soil permeability and must be evaluated. The adverse influence of sodium on soil permeability has been recognized for many years. But in many cases the evaluation of the sodium influence alone has proven to be in error basically because the interaction of three factors determines a water's long term influence on soil permeability. These factors are 1) sodium content relative to calcium and magnesium; 2) bicarbonate and carbonate content, and 3) the total salt concentration of the water. A simultaneous analysis of these has been applied to soils before but only recently has been applied to estimating the permeability hazard of irrigation waters to soils (Rhoades,1972).

3. Toxicity: A toxicity problem occurs when certain constituents in the water are taken up by the crop and accumulate in amounts that result in a reduced yield. This is usually related to one or more specific ions in the water namely boron, chloride and sodium.

4. Miscellaneous: Various other problems related to irrigation water quality occur with sufficient frequency that they should be specifically noted. These include excessive vegetative growth, lodging and delayed crop maturity resulting from excessive nitrogen in the water supply, white deposits on fruit or leaves due to sprinkler irrigation with high bicarbonate water and suspected abnormalities indicated by an unusual pH of the water.

Water quality and drainage problems are very often interrelated and adequate control of a potentially damaging water table is recognized as an essential requirement to successful long term irrigated agriculture. Salts will accumulate in the upper portions of a water table, and if water tables are as close as two meters from the soil surface they can become an important contributing source of additional salts in the crop root zone. When uncontrolled water tables exist within the two meter depth, salinity problems have occurred, even where irrigation water quality is good. With high water tables of poor quality, salts can be expected to accumulate rapidly in the crop root zone whereas with good quality groundwater they will still accumulate but at a much slower rate.

APPROACH TO EVALUATING QUALITY

Irrigation water quality refers to its suitability for use. A good quality water has the potential to allow maximum yield under good soil and water management practices. However, with poor quality water, soil and cropping problems can be expected to develop which will reduce yields unless special management practices are adopted to maintain or restore maximum production capability under the given set of conditions.

The suitability of a water, from a quality standpoint, is determined by its potential to cause problems and is related to the special management practices needed or the yield reduction caused. Solution in most cases is at the farm level, meaning the evaluation must be done in terms of the specific use and potential hazard to crop production under the existing management capability and farm situation.

In this paper, this type of problem solution approach has been taken. It evaluates the most common problems encountered and the steps necessary to maintain an acceptable level of agricultural production with the available water supply. Water quality problems, though often complex, generally occur in the four general categories previously discussed: salinity, permeability, toxicity, and miscellaneous. Each may affect the crop singly or in a combination of two or more. Such a combination may be more difficult to solve and may affect crop production more severely than a single problem acting by itself.

If the problems do occur in combination, the solution is more easily evaluated and understood if considered on a one-problem-at-a-time basis. Therefore the GUIDELINES and discussion which follow will consider each problem and its solution separately. By this procedure, a number of factors can be evaluated for each of the problem areas, such as:

1. the level of salts in the water that can be expected to cause a certain type of problem;

2. the mechanism of soil-water-plant interactions that cause the loss in production;

3. the severity of the problem that can be expected following long term use of the water;

4. the management alternatives that are available to prevent, correct or delay the onset of the problem.

WATER QUALITY EVALUATION

The initial step in determining the suitability of a water supply for irrigation use is to compare the water's quality against reported experiences. This evaluation can be made on a problem-by-problem basis if certain broad assumptions are made about the average conditions of use. In this section, the GUIDELINES for such a preliminary comparative evaluation of the potential of a water are presented. However, it is not enough to point out the limitations of a water supply without also pointing out methods to overcome or live with these limitations. In subsequent sections, the management alternatives available to adjust to or correct the potential problem are discussed.

GUIDELINES for Interpretation of Water Quality for Irrigation

GUIDELINES to evaluate water quality for irrigation using the problem approach are given in Table 1. They are limited to the various aspects of irrigation water quality that are normally encountered and which materially affect crop production. Emphasis is on the long term dominating influence of the water's quality on the soil-water-plant system as it affects crop production and soil and water management. The four most common problem areas are considered.

These GUIDELINES are practical and usable in general irrigated agriculture for evaluation of the more common constituents in surface waters, underground waters, drainage waters and sewage effluents. They are not intended however to evaluate the more unusual or special constituents sometimes found in waste waters such as pesticides and trace metals. Values for trace metal concentrations in irrigation waters, however, are given in another section along with salinity and trace element limitations for animal drinking water.

The GUIDELINES of Table 1 are based on certain assumptions which are given in the pages immediately following the table. These should be clearly understood.

To use the GUIDELINES, certain laboratory determinations and calculations are needed. The laboratory determinations needed along with a description of the symbols used in the GUIDELINES are given in Table 2. The adjusted sodium adsorption ratio (adj. SAR) should also be calculated from the laboratory determinations. The calculation procedure is given in Table 3.

Analytical procedures for the laboratory determinations are discussed in USDA Handbook 60 (1954), FAO Soils Bulletin 10 (Dewis and Freitas, 1970), and Standard Methods of the American Water Works Association (1971). These or other recognized procedures for analysis should be followed. It is also very important to obtain representative samples to ensure the usability of the determinations made.

Use of the GUIDELINES

In the preceding general discussion and GUIDELINES of Table 1, the basic information needed for a field evaluation of the suitability of a water for irrigation has been presented. This should allow a determination that water "A" having constituents "X, Y and Z" in concentrations shown by laboratory analysis does or does not have a potential to limit crop production. Where limitations are indicated, the water may still be usable providing certain management steps are taken to alleviate the problem. These various solutions are discussed in the subsequent sections and several examples are given in order to illustrate better how the GUIDELINES can be used.

The GUIDELINES of Table 1 are a management tool and, as with all laboratory methods and interpretative tools in agriculture, they are developed to help the trained field man or scientist to better understand, characterize, interpret, and hopefully improve the soil or plant response under a given set of conditions. Therefore, the user must constantly guard against drawing unwarranted conclusions based strictly on laboratory results alone. Laboratory data must be adequately related to field conditions or confirmed and tested by field trials or experience. If used in this spirit and remembering the basic assumption, the GUIDELINES should be a useful tool for the preliminary evaluation of the suitability of a water supply for irrigation.

Assumptions in the GUIDELINES

The water quality GUIDELINES presented in Table 1 are intended to cover a wide range of conditions in irrigated agriculture and incorporate the newer concepts in soil-water-plant relationships as recently developed. However, several basic assumptions must be made to better define the range of usability of these GUIDELINES. They may need adjustment or a new set prepared if the water is used under conditions which are greatly different from these stated conditions or assumptions. If the assumptions are understood, the GUIDELINES of Table 1 should be useful as a practical guide to evaluate the suitability of a water for irrigation. The basic assumptions in these GUIDELINES are:

1. Use of Water: The soil texture is sandy loam to clay loam, with good internal drainage. The climate is semi-arid to arid where effective annual rainfall is low [3]. These guides therefore may need adjustment for a monsoon climate or for areas where high precipitation occurs part of the year. Drainage is assumed to be good and no uncontrolled shallow water table is present. Full production capability of all crops is assumed when the GUIDELINES indicate water quality is not a problem. The existence of a potential problem indicates the use of certain tolerant crops may be necessary to maintain full production capability and does not indicate the water is unsuitable for use on any crop.

2. Methods and Timing of Irrigations: Surface and sprinkler methods of irrigation are assumed, including flood, basin, strip-check, furrow, corrugations and sprinklers, or any other which applies water on an "as needed" basis. This assumes that the crop utilizes a considerable portion of the stored soil water before the next irrigation. With these irrigation methods about 15% of the applied water is assumed to percolate below the rooting depth. The GUIDELINES are believed to be too restrictive for drip (trickle) irrigation and high frequency (near daily) sprinkler irrigation. They may need to be modified for subsurface irrigation.

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[3] Effective rainfall is the amount of precipitation that is useful in meeting the crop water demand or the leaching requirement.

TABLE 1 - GUIDELINES FOR INTERPRETATION OF WATER QUALITY FOR IRRIGATION

IRRIGATION PROBLEM	DEGREE OF PROBLEM		
	No Problem	Increasing Problem	Severe Problem
SALINITY - affects water availability to crop			
ECw (mmhos/cm)	< 0.75	0.75 - 3.0	> 3.0
PERMEABILITY - affects rate of infiltration of the water into and through soil			
ECw (mmhos/cm)	> 0.5	0.5 - 0.2	< 0.2
adj.SAR[1/][2/]			
Montmorillonite (2:1 crystal lattice)	< 6	6 - 9[3/]	> 9
Illite-Vermiculite (2:1 crystal lattice)	< 8	8 - 16[3/]	>16
Kaolinite-sesquioxides (1:1 crystal lattice)	<16	16 - 24[3/]	>24
SPECIFIC ION TOXICITY - affects sensitive crops			
Sodium[4/][5/] (adj.SAR)	< 3	3 - 9	> 9
Chloride[4/][5/] (meq/l)	< 4	4 - 10	>10
Boron (mg/l)	< 0.75	0.75 - 2.0	> 2.0
MISCELLANEOUS EFFECTS - affects susceptible crops			
NO_3-N (or) NH_4-N (mg/l)	< 5	5 - 30	>30
HCO_3 (meq/l) [overhead sprinkling]	< 1.5	1.5 - 8.5	> 8.5
pH	Normal Range= 6.5 to 8.4		

[1/] adj.SAR means adjusted Sodium Absorption Ratio and can be calculated using the procedure given in Table 3.

[2/] Values presented are for the dominant type of clay mineral present in the soil since structural stability varies between the various clay types (Rawlings, 1966 and Rhoades, 1975). Problems are less likely to develop if water salinity is high; more likely to develop if water salinity is low.

[3/] Use the lower range if ECw <.4 mmhos/cm;
use the intermediate range if ECw = 0.4 - 1.6 mmhos/cm;
use upper limit if ECw >1.6. mmhos/cm

< means less than
> means more than

[4/] Most tree crops and woody ornamentals are sensitive to sodium and chloride (use values shown). Most annual crops are not sensitive (use the salinity tolerance tables [Table 5]).

[5/] With sprinkler irrigation on sensitive crops, sodium or chloride in excess of 3 meq/l under certain conditions has resulted in excessive leaf absorption and crop damage.

TABLE 2 - LABORATORY DETERMINATIONS NEEDED TO EVALUATE WATER QUALITY

Laboratory Determination	Reporting Symbol	Reporting Units 1/	Equivalent Weight
Electrical conductivity	ECw	mmhos/cm	-
Calcium	Ca	meq/l	20
Magnesium	Mg	meq/l	12.2
Sodium	Na	meq/l	23
Carbonate	CO_3	meq/l	30
Bicarbonate	HCO_3	meq/l	61
Chloride	Cl	meq/l	35.4
Sulphate	SO_4	meq/l	48
Boron	B	mg/l	-
Nitrate-Nitrogen 2/	NO_3-N	mg/l	14
Acidity-Alkalinity	pH	pH 3/	-
Adjusted Sodium Adsorption Ratio	adj.SAR 4/	-	-
Potassium 5/	K	meq/l	39.1
Lithium 5/	Li	mg/l	7
Iron 5/	Fe	mg/l	-
Ammonium-Nitrogen 2/ 5/	NH_4-N	mg/l	14
Phosphate Phosphorous 5/	PO_4-P	mg/l	-

1/ mmhos/cm = millimhos/cm at 25°C; (mmhos/cm X 640 ≃ mg/l)
meq/l = milliequivalents per litre;
mg/l = milligrams per litre

2/ NO_3-N means nitrogen in the form of NO_3 while NH_4-N means nitrogen in the form NH_4. Reported as N in mg/l.

3/ Acidity (pH 1-7)
Alkalinity (pH 7-14)
Neutral (pH 7.0)

4/ Calculation procedures given in Table 3.

5/ Special situations only.

TABLE 3 - CALCULATION OF adj.SAR

The adjusted Sodium Adsorption Ratio (adj.SAR) is calculated from the following equation 1/ 2/:

$$\text{adj.SAR} = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \left[1 + (8.4 - pHc) \right]$$

where Na, Ca and Mg are in meq/l from the water analysis and pHc is calculated using the tables given below which relate to the concentration values from the water analysis. The table values are then substituted in the pHc equation:

$$pHc = (pK'_2 - pK'_c) + p(Ca+Mg) + p(Alk)$$

---Tables for calculating pHc ---------------------------------------

$$\left.\begin{array}{l} (pK'_2-pK'_c) \text{ is obtained from using the sum of } Ca+Mg+Na \text{ in meq/l} \\ p(Ca+Mg) \text{ is obtained from using the sum of } Ca+Mg \text{ in meq/l} \\ p(Alk) \text{ is obtained from using the sum of } CO_3+HCO_3 \text{ in meq/l} \end{array}\right\} \begin{array}{l}\text{Obtained} \\ \text{from} \\ \text{water} \\ \text{analysis}\end{array}$$

Sum of Concentration (meq/l)	$pK'_2-pK'_c$	p(Ca+Mg)	p(Alk)
.05	2.0	4.6	4.3
.10	2.0	4.3	4.0
.15	2.0	4.1	3.8
.20	2.0	4.0	3.7
.25	2.0	3.9	3.6
.30	2.0	3.8	3.5
.40	2.0	3.7	3.4
.50	2.1	3.6	3.3
.75	2.1	3.4	3.1
1.00	2.1	3.3	3.0
1.25	2.1	3.2	2.9
1.5	2.1	3.1	2.8
2.0	2.2	3.0	2.7
2.5	2.2	2.9	2.6
3.0	2.2	2.8	2.5
4.0	2.2	2.7	2.4
5.0	2.2	2.6	2.3
6.0	2.2	2.5	2.2
8.0	2.3	2.4	2.1
10.0	2.3	2.3	2.0
12.5	2.3	2.2	1.9
15.0	2.3	2.1	1.8
20.0	2.4	2.0	1.7
30.0	2.4	1.8	1.5
50.0	2.5	1.6	1.3
80.0	2.5	1.4	1.1

1/ A nomogram for determining $Na \Big/ \sqrt{\frac{Ca+Mg}{2}}$ is presented in Appendix B.

2/ pHc is a theoretical, calculated pH of the irrigation water in contact with lime and in equilibrium with soil CO_2.

TABLE 3. CALCULATION OF adj.SAR (continued)

Example pHc Calculation:

Given: (from the water analysis)

Ca	=	2.32 meq/l	CO_3	=	0.42 meq/l
Mg	=	1.44 "	HCO_3	=	3.66
Na	=	7.73 "			
			CO_3+HCO_3	=	4.08 meq/l
Ca+Mg+Na	=	11.49 meq/l			

From the Tables and Using the equation

$$pHc = (pK'_2 - pK'_c) + p(Ca+Mg) + p(Alk)$$

Calculate pHc as follows:

$pK'_2 - pK'_c$ = 2.3 - - - from sum of Na+Ca+Mg= 11.5 in column 1 and read for $pK'_2 - pK'_c$ in column 2

p(Ca+Mg) = 2.7 - - - from sum of (Ca+Mg)= 3.8 in column 1 and read for p(Ca+Mg) in column 3

pAlk = 2.4 - - - from sum of (CO_3+HCO_3)= 4.1 in column 1 and read for pAlk in column 4

pHc = 7.4

Substituting Na= 7.73, Ca+Mg= 3.76, and pHc= 7.4 in the adj.SAR equation as given above

$$adj.SAR = \frac{7.73}{\sqrt{\frac{3.76}{2}}} \left[1 + (8.4 - 7.4)\right]$$

$$adj.SAR = 5.64(2.0) = \underline{\underline{11.3}}$$

NOTE: Values of pHc above 8.4 indicate a tendency to dissolve lime from the soil through which the water moves; values below 8.4 indicate a tendency to precipitate lime from the water applied.

(Ref. L.V. Wilcox, U.S. Salinity Laboratory, Mimeo Dec. 30, 1966)

3. Uptake of Water by Crops: Uptake of water by the crop takes place from wherever water is most readily available in the rooting depth. This is normally about 40% from the upper one-quarter of the root zone, 30% from the second quarter, 20% from the third quarter, and 10% from the lowest quarter. Each irrigation will leach the upper soil area and maintain it at a relatively low salinity. Salinity will usually increase with depth and be greatest at the lower part of the rooting area. The average salt concentration of the soil solution of the rooting depth is assumed to be three times the concentration of the salts in the applied water and is believed to be representative of the salinity to which the crop responds. This corresponds to a leaching fraction of 15% on the basis of the 40-30-20-10% uptake of water by the crop and average root zone salinity.

The leached salts will be removed from the upper root zone and may accumulate to some extent in the lower root zone. Thus the salinity of the lower root zone is considered to be of less importance as long as the crop is relatively well supplied with moisture in the upper, "more active", root zone. The leaching requirement will control salts in this lower root zone.

4. Degree of Problem: The division of Table 1 into "No Problem," "Increasing Problem" and "Severe Problem" is somewhat arbitrary since changes occur gradually and there is no clear-cut breaking point. Changes of 10 to 20% above or below the GUIDELINE values may have little significance if considered in proper perspective with other factors affecting yield. Many field studies and observations, as well as carefully controlled research experiments were used as a basis for this division. The divisions have proven to be practical under production agriculture conditions.

Ordinarily no soil or cropping problem due to water quality would be experienced or recognized when using water containing less than the values shown for "No Problem" in Table 1. On the other hand, if water is used which equals or exceeds the values shown for the "Severe Problem," the water user would commonly experience soil or cropping problems associated with using this poor quality water. With water quality values between these guides, a gradually "Increasing Problem" should be experienced as the water quality deteriorates.

Large deviations from these assumptions might make it unsafe to use water which would otherwise be considered safe, or conversely, make it safe to use water which, under the assumed conditions, would be considered hazardous or of doubtful quality. Where sufficient experience, field trials, research or observations are available the GUIDELINES can be modified to fit more closely to local conditions. Specific conditions that may modify these values include the leaching fraction, the conditions of drainage, method of irrigation, the climate and rainfall, physical soil conditions, tolerance to salinity of crops grown, and the chemical properties of the soil.

PART II PROBLEM SOLUTION

PROBLEM CONSIDERATION

The preceding brief discussion and Tables 1-3 have presented the basic tools for evaluating the suitability of a water for irrigation. If a potential problem is predicted practices may need to be adopted that will delay, correct, or prevent its occurrence. Evaluating the management alternatives available to control the potential problem is therefore the second step in gaining maximum utilization of a given water supply. In the following sections each of the four problem areas shown in Table 1 will be reviewed, first as to its general cause, second, as to how the Guidelines are used to predict a potential problem (with examples) and, third, as to what management alternatives are available to help correct or prevent the occurrence.

For the sake of brevity, many of the sections of Part II in Paper 29 are omitted here. The portions deemed essential to the presentation are included in this text.

SALINITY PROBLEM DISCUSSION

Salinity Problem Evaluation

The presence or absence of a potential salinity problem is evaluated from the electrical conductivity of the irrigation water (ECw) as reported in the water analysis. ECw is reported in millimhos per centimeter (mmhos/cm) and by itself is usually an adequate measure of the potential salinity problem.

Management Alternatives for Salinity Problems

The major objective in choosing a management procedure to overcome a salinity problem is to improve soil water availability to the crop. Some of the management practices include:

1. irrigate more frequently to maintain a more adequate soil water supply to the crop;

2. plant crops that are tolerant of an existing or potential salinity problem;

3. routinely use extra water to satisfy the leaching requirement;

4. change method of irrigation to one that will give better salt control;

5. change cultural practices.

More drastic practices to improve or restore productivity of a salt-affected soil might include:

1. leach as needed to reduce concentration of accumulated salts;
2. improve the uniformity of slope or level of land to allow for more uniform water application;
3. modify soil profile to improve downward water percolation;
4. establish artificial drainage if water tables are a problem;
5. change water supply.

Crop Selection

There is an approximate 10-fold range in salt tolerance of agricultural crops. This wide choice of crops greatly expands the usable range of water salinity for irrigation and emphasizes the fact that quality is specific for the intended use.

If a potential salinity problem is indicated by the GUIDELINES, suitable crops can often be selected that are tolerant to the expected salinity. Crop tolerance tables for representative field, forage, vegetable and tree crops are given in Table 4. These incorporate older data from the crop tolerance tables of the U.S. Salinity Laboratory (USDA, 1954), data of Bernstein (1964), and from the University of California Committee of Consultants (1974) but have recently been updated based on data of Maas and Hoffman (in press).

The tables now include the expected yield reduction of 0, 10, 25 or 50% due to effects of either increasing soil salinity (ECe) or to comparable increases in irrigation water salinity (ECw). The conversion from the soil salinity (ECe) to comparable water salinity assumes that the salinity of the irrigation water will concentrate three times in becoming soil water (ECw x 3 = ECsw) and that the soil salinity (ECe) reported as a saturation extract is one-half the salinity of the soil water (ECsw x 0.5 = ECe).

The tables also include the suggested maximum ECe at which reduction in yield would be 100% (if the entire root zone were at this salinity, the crop could not extract water and growth would stop). The maximum ECe value is obtained by extrapolating the decrease from the 0-10-25-50% yield reduction values to 100%. This maximum ECe value is used in the new method of calculating the Leaching Requirement (LR).

TABLE 4.

CROP TOLERANCE TABLES[1] - FIELD CROPS

CROP	Expected Yield Reduction[2] at EC_e or EC_w indicated												MAXIMUM
	0%			10%			25%			50%			
	ECe[3]	ECw[4]	LR[5]	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECdw[6]
Barley[7] (Hordeum vulgare)	8.0[7]	5.3	10%	10	6.7	12%	13	8.7	15%	18	12	21%	56
Cotton (Gossypium hirsutum)	7.7	5.1	10%	9.6	6.4	12%	13	8.3	15%	17	12	21%	54
Sugarbeet (Beta vulgaris)	7.0[7]	4.7	10%	8.7	5.8	12%	11	7.5	16%	15	10	21%	48
Wheat[7] [8] (Triticum aestivum)	6.0[7]	4.0	10%	7.4	4.9	12%	9.5	6.4	16%	13	8.7	22%	40
Safflower (Carthamus tinctorius)	5.3	3.5	12%	6.2	4.1	14%	7.6	5.0	17%	9.9	6.6	23%	29
Soybean (Glycine max)	5.0	3.3	17%	5.5	3.7	18%	6.2	4.2	21%	7.5	5.0	25%	20
Sorghum (Sorghum bicolor)	4.0	2.7	7%	5.1	3.4	9%	7.2	4.8	13%	11	7.2	20%	36
Groundnut (Arachis hypogaea)	3.2	2.1	16%	3.5	2.4	18%	4.1	2.7	21%	4.9	3.3	25%	13
Rice (paddy) (Ozyza sativa)	3.0	2.0	9%	3.8	2.6	11%	5.1	3.4	15%	7.2	4.8	21%	23
Sesbania (Sesbania macrocarpa)	2.3	1.5	6%	3.7	2.5	8%	5.9	3.9	12%	9.4	6.3	19%	33
Corn (grain) (Zea mays)	1.7	1.1	6%	2.5	1.7	8%	3.8	2.5	13%	5.9	3.9	20%	20
Flax (Linum usitatissimum)	1.7	1.1	6%	2.5	1.7	8%	3.8	2.5	13%	5.9	3.9	20%	20
Broadbean (Vicia faba)	1.6	1.1	4%	2.6	1.8	7%	4.2	2.0	12%	6.8	4.5	19%	24
Cowpea (Vigna sinensis)	1.3	0.9	5%	2.0	1.3	8%	3.1	2.1	12%	4.9	3.2	19%	17
Beans (field) (Phaseolus vulgaris)	1.0	0.7	5%	1.5	1.0	8%	2.3	1.5	12%	3.6	2.4	19%	13

TABLE 4. (continued)

VEGETABLE CROPS

CROP	Expected Yield Reduction[2] at EC_e or EC_w indicated												MAXIMUM
	0%			10%			25%			50%			
	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECdw
Beets[7] (Beta vulgaris)	4.0	2.7	9%	5.1	3.4	11%	6.8	4.5	15%	9.6	6.4	21%	30
Broccoli (Brassica italica)	2.8	1.9	7%	3.9	2.6	10%	5.5	3.7	14%	8.2	5.5	20%	27
Tomato (Lycopersicon esculentum)	2.5	1.7	7%	3.5	2.3	9%	5.0	3.4	13%	7.6	5.0	20%	25
Cucumber (Cucumis sativus)	2.5	1.7	8%	3.3	2.2	11%	4.4	2.9	15%	6.3	4.2	21%	20
Cantaloupe (Cucumis melo)	2.2	1.5	5%	3.6	2.4	7%	5.7	3.8	12%	9.1	6.1	19%	32
Spinach (spinacia oleracea)	2.0	1.3	4%	3.3	2.2	7%	5.3	3.5	12%	8.6	5.7	19%	30
Cabbage (Brassica oleracea capitata)	1.8	1.2	5%	2.8	1.9	8%	4.4	2.9	12%	7.0	4.6	19%	24
Potato (Solanum tuberosum)	1.7	1.1	6%	2.5	1.7	8%	3.8	2.5	13%	5.9	3.9	20%	20
Sweet corn (Zea mays)	1.7	1.1	6%	2.5	1.7	8%	3.8	2.5	13%	5.9	3.9	20%	20
Sweet potato (Ipomea batatas)	1.5	1.0	5%	2.4	1.6	8%	3.8	2.5	12%	6.0	4.0	19%	21
Pepper (Capsicum frutescens)	1.5	1.0	6%	2.2	1.5	9%	3.3	2.2	13%	5.1	3.4	20%	17
Lettuce (Lactuca sativa)	1.3	0.9	5%	2.1	1.4	8%	3.2	2.1	12%	5.2	3.4	19%	18
Radish (Raphanus sativas)	1.2	0.8	4%	2.0	1.3	7%	3.1	2.1	12%	5.0	3.4	19%	18
Onion (Allium cepa)	1.2	0.8	5%	1.8	1.2	8%	2.8	1.8	12%	4.3	2.9	19%	15
Carrot (Daucus carota)	1.0	0.7	4%	1.7	1.1	7%	2.8	1.9	12%	4.6	3.1	19%	16
Beans (Phaseolus vulgaris)	1.0	0.7	6%	1.5	1.0	8%	2.3	1.5	12%	3.6	2.4	19%	12.5

TABLE 4. (continued)

FRUIT CROPS

CROP	Expected Yield Reduction[2/] at EC_e or EC_w indicated												MAXIMUM
	0%			10%			25%			50%			
	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECdw
Date palm (Phoenix dactylifera)	4.0	2.7	4%	6.8	4.5	7%	10.9	7.3	11%	17.9	12	19%	64
Fig (Ficus carica) Olive (Olea europaea) Pomegranate (Puncia granatum)	2.7	1.8	6%	3.8	2.6	9%	5.5	3.7	13%	8.4	5.6	20%	28
Grapefruit (Citrus paradisi)	1.8	1.2	8%	2.4	1.6	10%	3.4	2.2	14%	4.9	3.3	21%	16
Orange (Citrus sinensis)	1.7	1.1	7%	2.3	1.6	10%	3.3	2.2	14%	4.8	3.2	20%	16
Lemon (Citrus limonea)	1.7	1.1	7%	2.3	1.6	10%	3.3	2.2	14%	4.8	3.2	20%	16
Apple (Pyrus malus) Pear (Pyrus communis)	1.7	1.0	6%	2.3	1.6	10%	3.3	2.2	14%	4.8	3.2	20%	16
Walnut (Juglans regia)	1.7	1.1	7%	2.3	1.6	10%	3.3	2.2	14%	4.8	3.2	20%	16
Peach (Prunus persica)	1.7	1.1	9%	2.2	1.4	11%	2.9	1.9	15%	4.1	2.7	21%	13
Apricot (Pyrus armeniaca)	1.6	1.1	9%	2.0	1.3	11%	2.6	1.8	15%	3.7	2.5	20%	12
Grape (Vitis spp.)	1.5	1.0	4%	2.5	1.7	7%	4.1	2.7	11%	6.7	4.5	19%	24
Almond (Prunus amygdalus)	1.5	1.0	7%	2.0	1.4	10%	2.8	1.9	13%	4.1	2.7	20%	14
Plum (Prunus domestica)	1.5	1.0	7%	2.1	1.4	10%	2.9	1.9	14%	4.3	2.8	20%	14
Blackberry (Rubus spp.)	1.5	1.0	8%	2.0	1.3	11%	2.6	1.8	15%	3.8	2.5	21%	12
Boysenberry (Rubus spp.)	1.5	1.0	8%	2.0	1.3	11%	2.6	1.8	15%	3.8	2.5	21%	12
Avocado (Persea americana)	1.3	0.9	7%	1.8	1.2	10%	2.5	1.7	15%	3.7	2.4	20%	12
Raspberry (Rubus idaeus)	1.0	0.7	6%	1.4	1.0	9%	2.1	1.4	13%	3.2	2.1	19%	11
Strawberry (Fragaria chiloensis)	1.0	0.7	8%	1.3	0.9	10%	1.8	1.2	15%	2.5	1.7	21%	8

TABLE 4. (continued)

FORAGE CROPS

CROP	Expected Yield Reduction[2] at ECe or ECw indicated												MAXIMUM
	0%			10%			25%			50%			
	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECdw
Tall wheat grass (Agropyron elongatum)	7.5	5.0	8%	9.9	6.6	10%	13.3	9.0	14%	19.4	13	21%	63
Wheat grass (fairway) (Agropyron elongatum)	7.5	5.0	11%	9.0	6.0	14%	11	7.4	17%	15	9.8	22%	44
Bermuda grass [9] (Cynodon dactylon)	6.9	4.6	10%	8.5	5.7	13%	10.8	7.2	16%	14.7	9.8	22%	45
Barley (hay) [7] (Hordeum vulgare)	6.0	4.0	10%	7.4	4.9	11%	9.5	6.3	16%	13.0	8.7	22%	40
Perennial rye grass (Lolium perenne)	5.6	3.7	10%	6.9	4.6	12%	8.9	5.9	16%	12.2	8.1	21%	38
Trefoil, birdsfoot [10] narrow leaf (L. corniculatus tenuifolius)	5.0	3.3	11%	6.0	4.0	13%	7.5	5.0	17%	10	6.7	22%	30
Harding grass (Phalaris tuberosa)	4.6	3.1	9%	5.9	3.9	11%	7.9	5.3	15%	11.1	7.4	21%	36
Tall fescue (Festula elatior)	3.9	2.6	6%	5.8	3.9	8%	8.6	5.7	12%	13.3	8.9	19%	46
Crested Wh. grass (Agropyron desertorum)	3.5	2.3	4%	6.0	4.0	7%	9.8	6.5	11%	16	11	19%	57
Vetch (Vicia sativa)	3.0	2.0	8%	3.9	2.6	11%	5.3	3.5	15%	7.6	5.0	21%	24
Sudan grass (Sorghum sudanense)	2.8	1.9	4%	5.1	3.4	7%	8.6	5.7	11%	14.4	9.6	18%	52
Wildrye, beardless (Elymus triticoides)	2.7	1.8	5%	4.4	2.9	7%	6.9	4.6	12%	11.0	7.4	19%	39
Trefoil, big (Lotus uliginosis)	2.3	1.5	10%	2.8	1.9	13%	3.6	2.4	16%	4.9	3.3	22%	15
Alfalfa (Medicago sativa)	2.0	1.3	4%	3.4	2.2	7%	5.4	3.6	12%	8.8	5.9	19%	31
Lovegrass [9] (Eragrostis spp.)	2.0	1.3	5%	3.2	2.1	8%	5.0	3.3	12%	8.0	5.3	19%	28

TABLE 4. (continued)

FORAGE CROPS (continued)

	Expected Yield Reduction2/ at EC_e or EC_w indicated												
	0%			10%			25%			50%			MAXIMUM
CROP	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECe	ECw	LR	ECdw
Corn (forage) (zea mays)	1.8	1.2	4%	3.2	2.1	7%	5.2	3.5	11%	8.6	5.7	18%	31
Clover, berseem (Trifolium alexandrinum)	1.5	1.0	3%	3.2	2.2	6%	5.9	3.9	10%	10.3	6.8	18%	38
Orchard grass (Dactylis glomerata)	1.5	1.0	3%	3.1	2.1	6%	5.5	3.7	11%	9.6	6.4	18%	35
Meadow Foxtail (Alopecurus pratensis)	1.5	1.0	4%	2.5	1.7	7%	4.1	2.7	11%	6.7	4.5	19%	24
Clover, alsike, ladino, red, strawberry (trifolium spp.)	1.5	1.0	5.5	2.3	1.6	8%	3.6	2.4	12%	5.7	3.8	19%	20

CROP TOLERANCE TABLES1/

1/ Based on data as reported by Maas and Hoffman (in press); Bernstein (1964), and University of California Committee of Consultants (1974).

2/ Expected yield reduction for the particular crop due to indicated salinity of soil or salinity of irrigation water.

3/ ECe means electrical conductivity of the saturation extract of the soil (USSL) reported in millimhos per centimeter at 25°C. Values reported are from Maas and Hoffman (in press) and Bernstein (1964).

4/ ECw means electrical conductivity of the irrigation water in millimhos per centimeter at 25°C. This assumes a 15 to 20% leaching fraction and an average salinity of soil water equal to about three times that of the irrigation water applied ($EC_{sw} = 3\ EC_w$) or about twice that of the soil saturation extract ($EC_{sw} = 2\ EC_e$). From the above, $EC_e = 1.5\ EC_w$.

TABLE 4. (continued) CROP TOLERANCE TABLES[1/] (continued)

5/ LR means leaching requirement or the minimum leaching fraction that can be relied upon to control salts within the tolerance of the particular crop grown and considering the quality of water used. LR is determined from the equation LR= EC_w/EC_{dw}[6/].

6/ Maximum ECdw is the maximum salinity of the percolating water draining from the root zone that can result due to removal of water by the particular crop to meet its water requirement for growth (if all the root zone soil water were at this maximum ECdw, yield reduction would be 100% since the crop would be unable to extract water from the very salty soil water). This is the value used as ECdw in the LR calculation (LR= EC_w/EDdw). For the given crop and quality of water indicated, application of irrigation water to exactly meet the evapotranspiration demand of crop plus the LR to control salt should result in maximum efficiency of water use. At this efficiency, percolating water draining from the root zone would be minimal as to quantity but at a maximum as to salinity and should approach the maximum EC_{dw} as shown on these crop tolerance tables. ECdw=2ECe

7/ Barley, wheat, sugar beets and several other crops are less tolerant of salts during germination and early seedling growth. For germination of beets, salinity of soil in the seed area should not exceed EC_e= 3 mmhos/cm; for barley and wheat, EC_e should not exceed EC_e= 4 or 5 mmhos/cm.

8/ Tolerance data may not apply to semi-dwarf varieties of wheat. These are often more tolerant.

9/ An average of Bermuda grass varieties. Suwanee and Coastal are about 20% more tolerant; common and Greenfield are about 20% less tolerant.

10/ Average of Boer, Wilman, Sand, and Weeping Lovegrass. Lehman appears about 50% more tolerant.

11/ Broad-leaf birdsfoot trefoil appears to be less tolerant than narrow leaf.

It must be recognized that actual production with water of the quality indicated can range from the full 100% potential down to zero, depending upon any one of many factors other than water quality. The values given in Table 4 represent the maximum production potential for the quality of water under assumed conditions of use.

The values suggested as tolerance limits to salinity of applied water (ECw) may seem high at first glance. However, comparing these suggested values with field trials using relatively poor quality waters, as reported for instance from Tunisia (UNESCO/UNDP, 1970), from Pakistan (WAPDA, 1974) and others, there appears to be reasonably good agreement on salinity tolerance of crops tested.

Timing of Leaching Irrigations. The timing of leachings does not appear to be critical provided crop tolerances are not exceeded for extended or critical periods of time. The leaching can be done at each irrigation, each few irrigations, once each year, or after longer intervals. Regardless of the method used, adequate soil and crop monitoring should be used. Soil and plant tissue analysis can be used as an aid to determine the need and timing of leachings.

Flexibility in the management choice may be limited but several management steps suggested here may possibly apply to the particular irrigation situation:

1. plant crops during the cool season instead of the warm season since LR is related to the ET demand;

2. plant more salt tolerant crops, thus reducing the water needed for leaching;

3. use irrigation methods such as sprinklers which apply water below the infiltration rate of the soil thus reducing water movement through large pores. This will require more irrigation time but uses less water than continuous ponding (Oster et al., 1972);

4. use alternate ponding and draining instead of continuous ponding (Oster et al., 1972);

5. wet the soil prior to the start of the winter rains where rainfall is insufficient to do a complete leaching. Even a little rainfall on a wet soil is efficient in leaching since the rain moves deeper into the soil, as well as providing high quality water to the upper root zone.

Soil conditions may prevent flexibility in how the leaching requirements are applied. If soil infiltration rates are low, leaching may need to be postponed until after cropping. The effects of fallow periods on soil salinization will need to be considered. Water availability may also prevent flexibility thus allowing only after-harvest or presowing leachings or scheduling of leachings outside periods of peak water requirements. Leaching outside peak water use periods will also reduce the design capacity of the distribution system and may influence drainage design factors as well.

Major Changes Sometimes Required for Salinity Control

Many management alternatives require relatively simple changes in soil, crop and water management. Other procedures are available, however, that involve major changes in operational procedures and may require special engineering and design considerations. These are often costly but may improve existing soil conditions and make efficient irrigation and crop management much easier.

1. Leaching to remove salts
2. Land grading
3. Profile modification
4. Establishing artificial drainage
5. Changing or blending water supplies

PERMEABILITY PROBLEM DISCUSSION

The Permeability Problem

A permeability problem occurs if the irrigation water does not enter the soil rapidly enough during an irrigation to replenish the soil with water needed by the crop before the next irrigation. The reduced permeability is generally a problem of the upper few soil but occasionally may occur at deeper depths. This results in a decreased water supply to the crop just as a salinity problem does - but for a different reason. Permeability reduces the quantity of water placed into storage while salinity reduces the availability of the water in storage.

Low Salinity Waters

Low salinity waters are corrosive and tend to deplete surface soils of readily soluble minerals and salts. They have a strong tendency to dissolve rapidly all sources of calcium from the surface soil causing the finer soil particles to disperse, to fill pore spaces and to seal the soil surface. Very low salinity waters ($EC_w < 0.2$ mmhos/cm) often result in soil permeability problems and the lower the EC_w, the greater the potential of a permeability problem.

High Sodium Waters

High sodium in the irrigation water can cause a severe soil permeability problem. Meeting the crop water demand under these conditions may become extremely difficult. In addition, other problems such as crop germination, soil aeration, disease and weed control due to surface water ponding and stagnation may need special consideration.

The most commonly used method to evaluate the potential has been the Sodium Adsorption Ratio (SAR) according to the equation:

$$\text{SAR} = \frac{\text{Na}}{\sqrt{\frac{\text{Ca+Mg}}{2}}} \quad \text{(USDA Handbook 60, 1954)}$$

where Na = Sodium in meq/l
Ca + Mg = Calcium plus magnesium in meq/l

For SAR values greater than 6 to 9, the irrigation water could be expected to cause a permeability problem on the shrinking-swelling types of soil.

Permeability problems, however, are also related to the carbonate (CO_3) and bicarbonate (HCO_3) content in the irrigation water and this is not considered in the SAR procedure. When drying of the soil occurs between irrigations, a part of the CO_3 and HCO_3 precipitates as Ca-$MgCO_3$ thus removing Ca and Mg from the soil water and increasing the relative proportion of Na which would increase the sodium hazard. This effect on soil permeability has been evaluated separately by the Residual Sodium Carbonate (RSC) method (Eaton, 1950; USDA, 1954). Values of RSC have been suggested (Wilcox et al., 1953) on which a water's suitability could be judged. Each of these methods (SAR and RSC) have been used to evaluate the permeability hazard independently of each other although considerable interaction between the ions was known to occur. Each has been useful and has been used in many parts of the world with varying degrees of success.

Recent research has added refinements to the previous concept of SAR and RSC, and a newer procedure is suggested. The GUIDELINES of Table 1 use this new procedure which employs a modification of the previous SAR and now called the adjusted Sodium Adsorption Ratio (adj.SAR) method. The older SAR procedure is modified to include changes in soil water composition that are expected to result due to certain combinations of water salts which will either dissolve lime from the soil, (adding calcium) or will result in deposition of lime from the soil water (reducing calcium). The adj.SAR is then related to predominant soil clay mineralogy as shown in Table 1. The adj.SAR is calculated using the semi-empirical equation as given in Table 3.

$$\text{adj.SAR} = \frac{\text{Na}}{\sqrt{\frac{\text{Ca+Mg}}{2}}} \left[1 + (8.4 - \text{pHc})\right]$$

This procedure will more correctly predict the potential for a soil permeability problem than do the older SAR and RSC procedures.

Management Alternatives for Permeability Problems

Since the permeability problem only reduces the volume of water placed into storage for crop use, there seems little need to take corrective action until either the crop water demand or the leaching requirement can no longer be satisfied. Other problems caused by reduced permeability, however, may force corrective action. Included are problems such as waterlogging, crusting or compaction, poor aeration and germination or excessive weed and disease problems. These may be just as important in reducing yields as is an actual water shortage to the crop due to poor soil permeability. Corrective practices available include both "chemical" and "physical" methods.

The suggested practices that maintain or bring about a beneficial change in the soil or water chemistry include:

1. using soil or water amendments (gypsum, sulphur, sulphuric acid, etc.);
2. blending or changing the irrigation water supply.

The physical methods include cultural practices that manipulate the soil to increase infiltration or reduce the rate of water flow over the soil and allow more "opportunity time" for infiltration:

1. irrigating more frequently;
2. cultivating and deep tillage;
3. increasing the time allotted (duration) for an irrigation;
4. changing direction of irrigation to reduce grade (slope) of the land;
5. collecting and re-circulating runoff water;
6. with sprinklers, matching rate of water application to soil infiltration rate; and
7. using organic residues.

TOXICITY PROBLEM DISCUSSION

The Toxicity Problem

A toxicity problem is different from the salinity and the permeability problems, in that a toxicity occurs within the crop itself as a result of the uptake and accumulation of certain constituents from the irrigation water and may occur even though salinity is low. The toxic constituents of concern are sodium, chloride or boron. They can reduce yields and cause crop failure. Not all crops are equally sensitive but most tree crops and other woody perennial-type plants are. Toxicity problems of sodium and chloride, however, can occur with almost any crop if concentrations are high enough. Toxicity problems often accompany and are a complicating part of a salinity or permeability problem. Sprinkler irrigation may cause special toxicity problems due to sodium and chloride being absorbed through the leaves. Other trace elements which may cause toxicities are discussed in a following section.

Sodium

Most tree crops and other woody-type perennial plants are particularly sensitive to low concentrations of sodium. Most annual crops are not so sensitive, but may be affected by higher concentrations.

Sodium sensitive crops include deciduous fruits, nuts, citrus, avocado and beans. The GUIDELINES of Table 1 use the adj.SAR to evaluate the sodium hazard of the irrigation water to these sensitive crops.

Boron

A wide range of crops have been tested for boron tolerance by using sand culture methods. These crops have been grouped as to relative tolerance to boron in Table 10.

Management Alternatives for Toxicity Problems

The toxicity problems occur at relatively low concentrations in the irrigation water. If sensitive crops are to be grown, certain management practices may be needed which either reduce the effective concentration of the toxic substances or make adjustments that improve production under existing concentrations.

Practices to reduce the effective concentration of toxic constituents include:

1. irrigate more frequently;

2. use additional water for leaching;

3. in the case of sodium toxicity, use an amendment, such as gypsum or sulphuric acid; and

4. change or blend water supplies.

Practices to adjust to existing conditions include:

1. plant crops less sensitive;

2. use additional nitrogen to maximize fertility of the soil for growth of a crop such as citrus;

3. improve water management where this is contributing to the toxicity problem by the inability to control and properly distribute water. This may include increased leaching fraction, periodic leaching, land grading, profile modification and artificial drainage as discussed under salinity problem control; and

4. special techniques to be used when irrigation is by sprinklers.

Special Toxicity Effects Due to Sprinkler Irrigation

Overhead sprinkling of certain crops can cause special toxicity problems not encountered when irrigating by other surface methods. Excess quantities of sodium and chloride can be absorbed through leaves wet by the sprinkler and can cause leaf burn and, in some severe cases, defoliation. This occurs primarily during periods of high temperatures and low humidity and with rotating type of sprinkler heads. In between rotations of the sprinkler, water evaporates and salts are concentrated. The leaves absorb appreciably more salts during this alternate wetting and drying cycle than if sprayed continuously.

The leaf burn or crop damage seems to be primarily of specific toxicity due to uptake and accumulation of sodium or chloride. Toxicity occurs with sensitive crops at relatively low sodium or chloride concentrations. Toxicity has been reported to occur on citrus in several irrigated valleys of California, at concentrations as low as 3 meq/l of either sodium or chloride in the irrigation water. With furrow or flood irrigation these same concentrations cause no toxicity effects or leaf burn (Harding et al., 1958). Slight damage has been reported for more tolerant crops such as alfalfa under extremely high evaporative conditions at ECw = 1.3 mmhos/cm containing 6 meq/l sodium and 7 meq/l chloride. In contrast, little or no damage has occurred with waters as high as ECw = 4.0 mmhos/cm where sodium was 24 meq/l and chloride was 37 meq/l when evaporation conditions were low (Nielson and Cannon, 1975). Several vegetable crops tested were fairly insensitive to foliar effect at very high concentrations in the semi-arid conditions of California (Ehlig and Bernstein, 1959).

Sprinkler irrigation at night: Night sprinkling has been surprisingly effective in reducing or eliminating the sodium and chloride toxicity due to foliar absorption. Humidity generally rises at night and winds may decrease.

Increase speed of rotation of sprinkler heads: Frequent or continuous wetting results in less absorption than intermittent wetting. Use of sprinkler heads that rotate at 1 revolution per minute or less are recommended. Changing the speed of rotation will probably involve a change of the sprinkler head.

MISCELLANEOUS PROBLEM DISCUSSION

Miscellaneous Problems

From the standpoint of the GUIDELINES, there are just a few specific miscellaneous problems mentioned. Only nitrogen and bicarbonate are considered here.

Management Alternatives for the Miscellaneous Problems

The management alternatives that are effective for waters high in nitrogen are:

1. plant crops that are not sensitive and which can effectively utilize the nitrogen from the irrigation water;

2. where an alternative water source is available, blend or change water supplies to reduce nitrogen to more acceptable levels;

3. use alternative water supplies or blend to acceptable concentrations during the critical growth stages of the crop. Crops are not sensitive to nitrogen at all stages of growth. Utilizing a high nitrogen content water as a fertilizer early in the season but blending or changing supplies during critical periods may be possible;

4. the nitrate and ammonium-nitrogen occuring in irrigation water is readily available to crops, therefore, fertilizer nitrogen rates supplied to crops should be reduced by an amount very nearly equal to that available from the water supply. Ammonium-nitrogen is seldom present at more than one mg/l unless ammonia fertilizer or sewage effluent is being added to the water; and

5. denitrification may be possible but is not often used.

Some of the management alternatives for correction of the white deposit due to bicarbonates would be the same as discussed under special toxicity effects due to sprinkler irrigation:

1. irrigate at night during critical periods;

2. if sprinklers rotate too slowly, increase the speed of rotation;

3. do not sprinkle during periods of very low humidity; and

4. change irrigation method.

SUMMARY

A field guide is presented for evaluating the suitability of waters for irrigation and obtaining maximum use from the available water supply. GUIDELINE values are suggested which relate to the general irrigation problems of salinity, permeability and specific ion toxicity. Discussions and examples are given along with possible management alternatives to deal with these problems.

Salinity is discussed from the standpoint of a reduction in soil water availability to the crop. New findings on the plant's response to salinity within its root zone have been incorporated into the GUIDELINES to improve the predictive capability. Updated crop tolerance values have recently become available and have been expanded to include crop tolerance to salinity of various irrigation waters. A method is also presented for calculating the minimum leaching requirement for the various crops and water qualities. Values calculated by this procedure represent potential water savings over presently used values.

Soil permeability problems are associated with low salinity water or a high sodium water. An improved method is presented to predict the potential of a reduction in the rate of water penetration into and through the soil. The effects of excessive sodium, of high bicarbonate or carbonate, and of total salt load of the water are taken into consideration. The method used is a modification of the sodium adsorption ratio (SAR) concept.

Specific ion toxicity is related to the effects of boron, sodium and chloride on sensitive crops. Other minor problems are discussed such as bicarbonate deposits from overhead sprinkling and production problems from high nutrient water. Tables showing recommended maximum concentrations of trace elements for irrigation waters and for toxic substances in drinking water for livestock are also presented.

This paper is intended to provide guidance in on-farm water management problems so that an understanding of these constraints can assist in developing the criteria for irrigation project preliminary planning, operation of an irrigation project or perhaps in the improvement of existing irrigation schemes. The GUIDELINES presented are based on experience in areas other than a given project area, therefore caution and a critical attitude should be taken when applying these to local conditions. The guides indicate the potential of a water for irrigation but the true suitability of a given water depends on the management capability of the water user and on the specific conditions of use. The guides should be useful in placing the water quality effects in perspective with the other factors affecting crop production with the ultimate goal of obtaining maximum production per unit of available water supply.

REFERENCES

Abrol, I. P., D. R. Bhumbla, and G. P. Bhanqqua. 1972. Some observations on the effect of groundwater table on soil salinization. Proc. Int. Symp. on New Developments in the Field of Salt Affected Soils, 4-9 December 1972. Min. of Agric., ARE, Cairo, p. 41-48.

AWWA (American Water Works Association). 1971. Standard methods for examination of water and wastewater. 13th Edition. APHA-AWWA-WPCF, New York.

Aceves, N.E., L. H. Stolzy, and G. R. Mehuys. 1975. Effects of soil osmotic potential produced with two salt species on plant water potential, growth and grain yield of wheat. Plant and Soil, 42:619-627.

Ayers, R. S. and R. L. Branson, eds. 1973. Nitrates in the upper Santa Anna River Basin in relation to groundwater pollution. Calif. Agric. Expt. Sta. Bull. 861, 60p.

Bernstein, L. and R. S. Ayers. 1955. Sloping seedbeds. In Calif. Agric., Nov., p. 8.

Bernstein, L., M. Fireman, and R. C. Reeve. 1955. Control of salinity in the Imperial Valley, California. USDA, ARS 41(4), 15p.

Bernstein, L. and M. Fireman. 1957 Laboratory studies on salt distribution in furrow irrigated soil with special reference to the pre-emergence period. Soil Science, 83:249-263.

Bernstein, L. 1964. Salt tolerance of plants. USDA Agric. Inf. Bull. 283. 23p.

Bernstein, L. 1965. Salt tolerance of fruit crops. USDA Agric. Inf. Bull. 292. 8p.

Bernstein, L. and L. E. Francois. 1973. Leaching requirement studies: Sensitivity of alfalfa to salinity of irrigation and drainage waters. Soil Sci. Soc. Amer. Proc. 37:931-943.

Bernstein, L., L. E. Francois, and R. A. Clark. 1974. Interactive effects of salinity and fertility on yields of grains and vegetables. Ag. J. 66:412-421.

Bernstein, L. and L. E. Francois. 1975. Effects of frequency of sprinkling with saline waters compared with daily drip irrigation. Agron. J. 67(2): 185-191.

Bouwer, H. 1969. Salt balance, irrigation efficiency and drainage design. Amer. Soc. Civil Eng., Proc. 95(IRI):153-170.

Bower, C. A. and L. V. Wilcox. 1965. Precipitation and solution of calcium carbonate in irrigation operations. Soil Sci. Soc. Proc. 29:93-94.

Bower, C. A., L. V. Wilcox, G. W. Akin, and Mary G. Keyes. 1965. An index of the tendency of $CaCO_3$ to precipitate from irrigation waters. Soil Sci. Soc. Amer. Proc. 29:91-92.

Bower, C. A., G. Ogata, and J. M. Tucker. 1967. Sodium hazard of irrigation waters as influenced by leaching fraction and by precipitation or solution of calcium carbonate. Soil Sci. 100:29-34.

Branson, R. L., C. D. Gustafson, A. W. Marsh, S. Davis, and R. A. Strohman. 1974. Monitoring soil salinity and leaf nutrient levels in a young avocado orchard under drip irrigation. Proc. Second Int. Drip Congress, San Diego, Calif., USA, p.364-369.

Brown, L. N. 1963. Planting of irrigation on the contour. Univ. Calif. Agric. Ext. Serv. Circ. 523.

Chapman, H. D. and P. F. Pratt. 1961. Methods of analysis for soils, plants and waters. Univ. Calif., Div. Agric. Sci.

Dewis, J. and F. Freitas. 1970. Physical and chemical methods of soil and water analysis. Soils Bulletin 10, FAO, Rome. 275p.

Dieleman, P. J., ed. 1963. Reclamation of salt affected soils in Iraq. International Institute for Land Reclamation and Improvement, Wageningen. Public. 11. 175p.

Doneen, L. D., ed. 1958. Quality of water for irrigation. Proc. Conference on Quality of Water for Irrigation, University of California. Water Resources Center Contribution 14. 208p.

Doneen, L. D. 1964. Water quality for agriculture. Dept. of Irrig., Univ. Calif., Davis. 48p.

Doneen, L. D. 1967. Water quality requirements for agriculture. The National Symposium on Quality Standards for National Waters. Educational Series No. 161. Univ. Mich., Ann Arbor, Mich., U.S.A. p.213-218.

Doneen, L. D. 1971. Irrigation practice and water management. Irrigation and Drainage Paper 1, FAO, Rome. 84p.

Doorenbos, J. and W. O. Pruitt. 1975. Crop water requirements. Irrigation and Drainage Paper 24, FAO, Rome. 179p.

Eaton, F. M. 1950. Significance of carbonates in irrigation waters. Soil Sci. 69:123-133.

Ehlig, C. F. and L. Bernstein. 1959. Foliar absorption of sodium and chloride as a factor in sprinkler irrigation. Proc. Amer. Soc. Hort. Sci. 74:661-670.

Ewart, G. Y. 1965. Defining osmotic pressure in salinity problems. Proc. 12th I.S.S.C.T. Congress, Puerto Rico. p. 82-89.

FAO. 1973. Trickle irrigation. Irrigation and Drainage Paper 14, FAO, Rome. 153p.

FAO. 1976. Prognosis of salinity and alkalinity. Soils Bulletin 31, FAO, Rome. (In press)

FAO-Unesco. 1973. Irrigation, drainage and salinity. An International Sourcebook. Paris, Unesco/Hutchinson and Co. London. 510 p.

Fireman, M. and R. L. Branson. 1965. Gypsum and other chemical amendments for soil improvement. Calif. Expt. Sta. and Ext. Serv. Leaflet 149. 4p.

Halsey, D. 1974. Growth and salt accumulation with desert drip irrigation. Calif. Citrograph, Dec. p. 47-48.

Hanna, A. B. and K. Al Talakani. 1970. Evaluation of water quality in Iraq. First Tech. Conf., Arab Fed. Agric. Engineers, Khartoum, Sudan. 29p. (In Arabic)

Harding, R. B., M. P. Miller, and M. Fireman. 1958. Absorption of salts by citrus leaves during sprinkling with water suitable for surface irrigation . Proc. Amer. Soc. Hort. Sci. 71:248-256.

Jacobsen, T. and R. M. Adams. 1958. Salt and silt in ancient Mesopatamian agriculture. Science. 128:1251-1258.

Kessler, J., ed. 1973. Drainage principles and applications II: Theories of field drainage and watershed runoff. International Institute for Land Reclamation and Improvement, Publication 16, 374p.

Kohler, K. O., Jr. 1953. Contour-furrow irrigation. U.S.D.A. Soil Conservation Service. Leaflet 324.

Langelier, W. F. 1936. The analytical control of anticorrosion water treatment. J. Amer. Waterworks Assn. 28:1500-1521.

Lunt, O. R., ed. 1963. Agricultural water quality research conference proceedings. Univ. Calif. Water Resources Center Report 5, 69p.

Maas, E. V. and G.J. Hoffman. 1976. Crop salt tolerance - current assessments. U. S. Salinity Laboratory publication. (In press)

Massoud, F. 1976. Guidelines for prognosis and monitoring of salinity and sodicity. FAO, Rome. (In preparation)

Marsh, A. W. 1974. Water use by drip and sprinkle irrigated avocados related to plant cover, evaporation and air temperature. Proc. Second Int. Drip Congress, San Diego, Calif., U.S.A., p. 346-350.

Mohamed, N. A. and F. Amer. 1972. Sodium carbonate formation in Ferhash area and possibility of biological dealkalization. Proc. Int. Symp. on New Developments in the Field of Salt Affected Soils, Dec. 4-9, 1972. Min. of Agric. ARE, Cairo. p. 346.

National Academy of Sciences and National Academy of Engineering. 1972. Water quality criteria. EPA-R3-73-033, 592p. (U. S. Government Printing Office, Washington, D.C.)

Nielson, R. F. and O. S. Cannon. 1975. Sprinkling with salty well water can cause problems. Utah Science, Agric. Expt. Sta., 36(2):61-63.

Oster, J. D., L. S. Willardson, and G. J. Hoffman. 1972. Sprinkling and ponding techniques for reclaiming saline soils. Transactions of the ASCE, 15(6):1115-1117.

Pearson, G.A. 1960. Tolerance of crops to exchangeable sodium. USDA Information Bulletin 216, 4p.

Pillsbury, A. F. 1968. Sprinkler irrigation. FAO Agricultural Development Paper 88, FAO, Rome.

Pratt, P. F. 1972. Quality criteria for trace elements in irrigation waters. Calif. Agric. Expt. Sta. 46p.

Pratt, P. F. 1974. Nitrate in effluents from irrigated lands. Annual Report to Nat. Sci. Found. from Kearney Found. of Soil Sci., Univ. Calif., 320 p.

Rawlings, R. 1966. An investigation into the causes of failures of farm dams in Brigalow Belt of Central Queensland. Bulletin 10, Water Research Foundation of Australia, New South Wales, Australia.

Reeve, R. C., A. F. Pillsbury, and L. V. Wilcox. 1955. Reclamation of a saline and high boron soil in the Coachella Valley of California. Univ. Calif., Hilgardia, 24(4):69-91.

Rhoades, J. D. 1968. Leaching requirement for exchangeable sodium control. Soil Sci. Soc. Amer. Proc. 32:652-656.

Rhoades, J. D. 1972. Quality of water for irrigation. Soil Sci. 113:277-284.

Rhoades, J. D., J. D. Oster, R. D. Ingvalson, J. M. Tucker, and M. Clark. 1973. Minimizing the salt burdens of irrigation drainage waters. J. Environ. Qual., 3:311-316.

Rhoades, J. D. Drainage for salinity control. *In* J. Van Schilfgaarde, ed., Drainage for agriculture. Amer. Soc. of Agronomy Monograph 17, p.443-462.

Rhoades, J. D. 1975. Personal communication, July 1975.

Rhoades, J. D. 1976. Personal communication, Feb. 1976.

Schofield, R. K. 1947. A ratio law governing the equilibrium of cations in the soil solution. Int. Congr. Pure Applied Chem., Proc. 11 (London, England), 3:257-261.

Sinha, B. K. and N. T. Singh. 1976. Salt distribution around roots of wheat under different transpiration rates. Plant and Soil, 44:141-147.

Van Hoorn, J. W. 1971. Quality of irrigation water, limits of use and prediction of long term effects. *In* Irrigation and Drainage Paper 7, Salinity Seminar Baghdad, FAO-UN, Rome, p.117-135.

Unesco-UNDP. 1970. Research and training on irrigation with saline water. Technical Report of UNDP Project Tunisia 5, 256p.

University of California Committee of Consultants. 1974. Guidelines for interpretation of water quality for agriculture, 13p.

USDA Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. USDA Handbook 60, 160p.

WAPDA. 1973. Effect of tubewell water of different salinities on soil condition and crop growth. West Pakistan Water and Power Development Authority, Publication 25, 94p.

WAPDA. 1974. Annual report of mona reclamation experiment project. West Pakistan Water and Power Development Authority, Publication 29, 160p.

Wilcox, C. V., G. Y. Blair, and C. A. Bower. 1953. Effect of bicarbonate on suitability of water for irrigation. Soil Sci. 77:259-266.

Wilcox, L. V. 1960. Boron injury to plant. USDA Bull. 211, 7p.

Wilcox, L. V. 1963. Factors for calculating the Sodium Adsorption Ratio (SAR). U. S. Salinity Laboratory Mimeo Report.

Wilcox, L. V. 1966. Tables for calculating the pHc values of water. Mimeo of U. S. Salinity Laboratory, 8p.

Yaron, B., E. Danfors, and Y. Vaadia. 1973. Arid zone irrigation, Ecological Studies Vol. 5, London.

BASIC PRINCIPLES FOR PROGNOSIS AND MONITORING OF SALINITY AND SODICITY

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INTRODUCTION

Though more and more investment is being made in irrigated land development projects, it often appears that the output from these lands does not materialize as expected. In most cases failures or setbacks are caused by the formation of salt affected soils in arid and semi-arid climates and also by inefficient water and soil management practices. Better selection of lands to be put under irrigation, adoption of sound and efficient soil, water and agronomic management practices, and early warning against salinity and sodicity hazards, through prognosis and monitoring procedures, are essential prerequisites for successful irrigation development. There is no doubt that protection is better than cure and that the right prediction gives a clear picture of what the future will be, consequently what precautions and actions should be taken. In this sense, prognosis and monitoring should be regarded as protective and remedial measures.

Prognosis and monitoring have only recently been given attention. It was in the Symposium on the Reclamation of Sodic and Soda - Saline Soils that Hungarian scientists (Szabolcs et al., 1969) presented the first systematic field study on the subject based on a predictive methodology. FAO, in cooperation with the ISSS Sub-Commission on Salt Affected Soils, organized an Expert Consultation on prognosis of salinity and alkalinity (FAO, 1976) with a view to drawing up guidelines for predicting and monitoring salinity and sodicity. This paper highlights the basic principles being considered for the preparation of these guidelines.

GLOBAL NEED FOR PROGNOSIS AND MONITORING

Salt affected soils are found in every continent (Table 1 in the Annex) (Massoud, 1974) but information on the exact areas degraded or their degree of deterioration is not available for all the countries affected. Szabolcs (1971) estimates that in Europe something over 27 million ha are salt affected and that the potentially affected areas are equal to or greater than the presently affected ones. It can be stated that about 7 percent of the total surface area of the world is covered by salt affected lands. Although the arable portion of this sizeable area is not exactly known, it is estimated that more than 50% of all irrigated lands of the world have been damaged by secondary salinization and/or sodication and waterlogging.

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The widespread occurrence of these potential hazards means that there is a global need for protective and remedial actions, where economically and technically feasible. Prognosis is mostly needed where arable and potentially salt affected soils exist. Areas already affected by salinity and sodicity, but undergoing reclamation and development, require monitoring more often than normal ones, to check on the effectiveness of soil improvement and the reliability of the reclamation procedures.

There may exist a few general or local methods for predicting salinity and sodicity, but a coordinated international guideline and a standardized methodology are lacking and needed (Szabolcs, 1976). Since salinity and sodicity are of common concern to multidisciplinary fields, the guidelines must be suitable to address to a wide audience, from planners to farm technicians. In general, the guidelines ought to be written in an easy technical language to be of practical use in the fight against the spread of salt affected soils.

BASIC CRITERIA AND PARAMETERS

The development of salt affected soils in irrigated or potentially irrigable areas involves the integrated effects of natural and man-made factors (Kovda, 1971; FAO/UNESCO, 1973). Under the natural factors comes the influence of the geomorphological, hydrological, hydrogeological, biological and climatic conditions. Soil and water management and agronomic practices reflect the influence of man. Moreover, each factor in turn is characterized by various parameters,and that accounts for their diversity and the complexity of the salinity and sodicity problems. Therefore, in analyzing such problems consideration should be given to that wide range of parameters and to the specific role played by each, individually or in combination with others.

In order to be able to predict whether a normal soil will develop into a salt affected one or vice-versa, the various parameters affecting salinization, sodication and the reverse processes should be assessed. One approach would be the evaluation of each of the most relevant parameters with a view to its actual or potential contribution to these processes. The other would be an assessment of the basic criteria indicative of these processes and how they are affected by various parameters. The latter approach, which has the advantage of being an integrated one, but at the same time is complex too, is now presented.

The basic criteria indicative of salinization and desalinization processes are salt movement and salt balance. Those indicative of sodication are the direct effect of exchangeable sodium on structural deterioration and soil permeability reduction, and the indirect specific effect on plants. Better understanding of these criteria requires knowledge of the origin and characteristics of the various salts and ions involved in these processes. This knowledge not only helps to visualize the origin of the problem as a natural or man-made phenomenon and the mechanisms of its formation, but also the conditions under which it could be regenerated. Enough material is available in many publications, including FAO/UNESCO (1973), on the origin, source and characteristics of salts. On the other hand, the basic criteria and the relevant parameters should be carefully investigated and monitored from a predictive point of view. It is felt, however, that this latter approach needs more emphasis and is therefore given here more elaborately.

SALINIZATION

Salt Movement and Accumulation

For prognosis and monitoring of salinity and sodicity, prediction and knowledge of the rate and direction of salt movement and accumulation, together with the assessment of the factors affecting these processes, are very essential. It could be simply stated that, for a given soil, the distribution of soluble salts and their accumulation in the soil profile are mainly controlled by the moisture regime and climatic conditions. As the soluble salts are transported within the soil mostly by water flow and partly by diffusion, their movement will be determined by the basic laws applicable to water movement and solute diffusion. Since the root zone in a cultivated soil is in a drying rather than a wetting state most of the time, except during and after irrigation or rainfall, the salts tend to move upward and accumulate especially in the presence of a continuing water supply,say from a water table. In other words, the process of salinization is more liable to occur and proceed, unless salts are pushed below the root zone or the salt concentration of the groundwater is diluted by efficient water management.

Among the most important parameters affecting water and salt movement in soil are the hydraulic conductivity (K) and diffusivity (D). They, however, vary with the soil characteristics, mainly continuity, stability,and size distribution of the pores and their degree of saturation with water (stratification, structure, texture,and moisture content). It is to be expected,then,that in a well aggregated soil desalinization can be more easily achieved than in soils that have unstable pore structure, are highly compacted or dense, and have a high portion of narrow pores. The presence of salts encourages aggregation and enhances water movement, while high exchangeable sodium in the absence of sufficient salts retards water movement and induces waterlogging. The most important characteristic of hydraulic conductivity is its dependence on the soil mositure tension, $K = f(\rho)$. Of the various empirical equations describing this relation, the most commonly employed ones are $K = a\,\rho^{-n}$ (Wind, 1955), and $K = a/b + \rho^{n}$ (Gardner, 1958) where a, b, and n are constants with the value of n about 2 for clay soils and 4 for sandy ones. More forms of this significant relation are cited by Raats and Gardner (1974).

For practical purposes, the contribution of diffusion to solute movement is negligibly small and very slow compared to mass flow (van der Molen, 1976).

Salt Balance

The possibility of predicting the direction and rate of solute movement has been demonstrated by the application of the basic laws governing water and solute transport. As to the amount of salts stored within a certain time in a given volume element of the soil, one has to know all the relationships of salt inputs and salt outputs, or what is known as the salt balance (Scofield, 1940). The same approach has also been used by Russian investigators since the late thirties in research and meliorative projects (Kovda, 1971). Since the salt balance is determined by the weighted effect of the different salt input and output sources (the solution volume times the solute concentration), precise assessment of the soil and water elements of the balance will give an account of the change in salinity in the period between monitoring dates, and consequently the trend in the salinity status.

A comprehensive form of the salt balance model that considers the various salt and water sources is:

$$(IC_i + PC_p + GC_g + AC_a + M + F) - (DC_d + NC_n + T + W) \pm S_eC_e \pm RC_r = \pm \Delta S$$

where I, P, G, A, D, N, S_e, R and C_i, C_p, C_g, C_a, C_d, C_n, C_e, and C_r are volumes and total salt concentration of irrigation, precipitation, ground, artesian, surface drainage, natural drainage (deep percolation), seepage and surface run-off waters, respectively. M is the amount of soluble salts derived from weathering of soil minerals or salt deposits, F is the soluble portion of fertilizers, chemical amendments and manures, T is the quantity of salts removed in the harvested crop,and W is the quantity of salts deposited from irrigation water in a limited solubility or unstable form. The quantities preceded by a positive sign are potential contributions to the salt input while those preceded by a negative sign are the removed quantities or outputs. Depending on the magnitude of each salt and water element and the relative importance of the various terms of the salt balance, the net change in the salt content (both soluble and exchangeable) of the area or soil body under investigation, Δ S, can be determined.

The contribution of the above components to the salt balance is not equal, even if they are all active and can be accurately assessed, and only a few of them are normally the major contributors. In monitoring and assessing each of these components, the numerous parameters affecting the water volume and/or salt concentration have to be taken into account as illustrated in the analyses of the following components.

Irrigation Water

For irrigated lands in arid and semi-arid regions, where salinity is most common, irrigation water is by far the main contributor to the soil moisture regime, especially in the absence of a shallow water table. When a normal water requirement of 10,000 m^3/ha/year is applied, 0.2 ton/ha of salts could be added by using a good quality water containing 200 ppm of soluble salts. Of course, the higher the salt concentration in the applied water, the higher the opportunity for soil salinization will be. The quantity of irrigation water, if in excess of that needed to replenish the soil reservoir to its field capacity usually leaches salts from the root zone, in a well drained soil, while if thinly spread over large areas salinization might occur. The method of irrigation, the uniformity of moisture distribution,and frequency of application are significant factors in monitoring irrigation water,especially in relation to the salt balance in the root zone. In flood or spate irrigation,salts tend to move away from the root zone; this also happens with properly managed sprinkler or drip irrigation systems. However, in the latter,salts concentrate midway between plants and at the wetting front between the lines of drip emitters (Bernstein and Francois, 1975). The uniformity of moisture distribution and, consequently, salts in soils irrigated with basins, borders,or furrows depend on the efficiency of the design of the system. As to the frequency effects, more frequent irrigation means keeping the soil relatively more moist and the salt solution less concentrated, i.e.,favorable salt balance.

Precipitation

The salt content in rainwater and snow is practically insignificant. In salt spray and precipitation close to coastal areas chloride concentration is highest at the coast line (several ppm) but decreases rapidly further inland. As to the quantity of rainfall, it is more often sufficient to take care of salt leaching in humid and sub-humid regions, but it is limited in arid and semi-arid zones. In arid regions,due to scarcity and unreliability of rains, unless salts are leached by irrigation, salinity build up can be expected. In semi-arid regions, although the amounts of rain are relatively higher (2,500-5,000 m^3/ha/year), the risk of salinization still exists, except under a Mediterranean climate where rain falls in a defined period sufficiently to leach salts from the previous season.

Seepage and Artesian Waters

The concentration of salts in seepage and artesian waters is highly dependent on their original mineralization and that of the strata or aquifer through which they seep or flow. The amount of seepage from irrigation networks is considerable. A loss from unlined convergence and distribution systems, as reported by Kraatz (1971), is about 40 to 50% of the total water diverted. Where the canals are lined by hard surface lining, roughly 60 to 80% of the total water lost from unlined canals can be saved. Similarly, due to the silting effect, seepage from old unlined canals is normally reduced to about 20% of that from new ones. The contribution of seepage to the development of salinity in an arid climate is common along the foot of a hill or natural terrace and in valleys,while in irrigated lands it is most apparent closer to water courses and in cultivated areas next to submerged rice fields.

Artesian water is a particular form of seepage water found under artesian pressure at a greater depth than the other seepage forms. Its significance comes from the continuous rise to the surface and difficulty to drain which is complicated by the obscurity of the sources of excess water (Luthin, 1957). As a result of continuous evaporation, the uninterrupted rising water becomes mineralized to a considerable depth and the problem becomes more serious if the groundwater was originally mineralized.

Shallow Groundwater

Of the major components of salt balance, the shallow groundwater can play a decisive role in developing an unfavorable salt balance and root environment. That role is related to the salt content and composition, the depth and fluctuation of the groundwater and is usually affected by the soil characteristics, water and soil management practices, tolerance of plants to waterlogging and salinity, and climate. Although man through misuse of water and soil resources is quite often the creator of the shallow water table, natural seepage and artesian flows are also sometimes involved. All these factors should be considered in monitoring and predicting salinity due to the shallow groundwater.

In this regard, the term "critical water table depth" is often mentioned and considered as the level above which water rising by capillarity will cause salinization of the soil arable horizons. Kovda (1973) relates this critical depth to the salt content of the groundwater in the arid zone and areas provided with irrigation and drainage as, respectively, being 2-2.5 m when the salt concentration is 10-15 g/l, and 1-1.5 m for a less mineralized groundwater, 1-2 g/l. The critical depth for a given upward flux (q) can be calculated provided the relations between soil moisture tension, hydraulic conductivity, and soil moisture content are known. Some critical depth values (Z_{max}) for illustrative soil parameters were calculated by van Schilfgaarde (1976) and found to be 75-100, 175-200 and 90-120 cm for loam, fine sandy loam, and sandy soils, respectively. When considering these values in monitoring and forecasting investigations, the depth at which q_{max} is maintained should be estimated and added to the critical depth to obtain the theoretical depth to water table. For bare soils, the critical depth coincides with the depth from the soil surface to the water table, but for cropped soils, the critical depth should be taken below an estimated active root zone.

The significance of the depth to water table comes from its influence on the capillary rise; the shallower the depth the higher the contribution of the groundwater to salinization will be. Generally, the decreasing trend of the maximum capillary rise in various uniform soils under a given evaporative demand follows the descending order, sandy loam, loam, clay loam and clay, medium and coarse sand. In many field situations and in particular for alluvial, stratified soils, the critical depth as calculated for homogeneous soils may have a limited application. The solution given by Varallyay (1974) to the problem of upward unsaturated flux in layered soils indicates that the upward capillary flux depends largely on the hydraulic conductivity and the thickness and sequence of horizons. Where the stratification conditions permit high hydraulic conductivity near the water table and far from it, as in clay over sand, the upward capillary flux will increase.

When monitoring water table level as a source of salinity one has to consider its cyclic nature and, therefore, information on the fluctuation cycle after irrigation and other seasonal variations should be obtained.

As to the rate of accumulation of soluble salts due to upward movement of groundwater, it can be obtained by multiplying the salt concentration of this water by the evaporation rate.

Evapotranspiration

Through evapotranspiration, ET, water is transferred from the soil and plants to the atmosphere, leaving salts behind. In bright sunshine, warm weather, and low relative humidity, as in arid and semi-arid regions, the opportunity for evaporation is high and, consequently, so is soil salinization. The rate of evaporation from a bare soil in contact with a water table depends on the depth to that level, the evaporativity of the atmosphere, and the transmitting property of the soil. Gardner and Fireman (1958) indicated that the evaporation rate decreases with increasing depth to water table and is limited by the external evaporative conditions where there is a shallow water table (less than 90 cm depth).

In cases where plants are growing in the presence of a water table acting as the main source of water supply, the equilibrium moisture depletion and salt concentration patterns due to ET and capillary rise depend on the evaporativity of the atmosphere, the activity of the plant and its rooting depth, the transmitting property of the soil, and the depth to water table. Of these factors, the difference between the rate of upward flux and that of ET determines the depth of moisture depletion and salt accumulation zone. The applicability of the solution given by Gardner (1958) to the unsaturated flow equation has proved to be valid in the presence of plant roots (Massoud, 1964; Manor, 1974). Generally, the depth to the boundary of maximum capillary rise and salt movement increases with increasing depth to water table. Soils with a better transmitting property, especially at low tensions, will transfer the salt with the liquid phase to a higher zone above the water table.

A third type of effect from evapotranspiration on moisture and salt patterns occurs with irrigation in the presence of a water table. Elgabaly and Naguib (1965) showed that the water table depth and salinity together with the irrigation regime for a given crop rotation are important factors that modify the salinity pattern due to ET and capillary rise.

Evapotranspiration from a cropped area is, in general, highly dependent on the soil characteristics, mainly those affecting its water content, transmission to the evaporative or absorption sites and subsequent loss to the atmosphere. As to the plant characteristics, the most significant is the degree of plant cover which is related to its stage of growth and cultural requirement. Variation in ET due to this factor is observed up to 50% cover.

Surface Drainage and Deep Percolating Waters

Under irrigation, the quantity of drained water depends on the amount of water added in excess of ET requirements (leaching fraction) and efficiency of irrigation. Besides losses by seepage from the main conveyance systems, on farm losses can range from 30 to 70% for surface irrigation methods (Keller, 1965). Losses due to evaporation and percolation are less for sprinkler, 15% (Christiansen and Davis, 1967) and no contribution to the drained water should be expected from drip irrigation.

Deep percolating water can remove excess salts far below the root zone without an immediate threat of soil salinization but the possibility of a gradual groundwater rise in deep strata should be foreseen depending on the percolating quantity and drainable porosity.

The quantity of water and concentration of salts can be easily monitored from drain discharges, but are rather difficult in cases of deep or natural drainage.

Surface Run-Off

Run-off comprehends the flow of water on the soil surface. In a properly designed irrigation system the contribution, with moderate slopes and a reasonable length of runs, is estimated to be only 10 to 15% of the water supplied to furrows or borders (Nugteren, 1973). However, the contribution is sizeable in the event of high intensity rain storms. As to the salt load in surface run-off water, it is affected by the salt content of the soil or surface salt crusts and the degree of slope. Under controlled irrigated agriculture, tailwater is usually discharged to surface drains and little change in the salt content of water flowing over the soil is to be expected (Reeve et al., 1955).

Salts Derived from Weathering, Fertilizers and Manures, Amendments and Crops

The change in the amount of salts derived from weathering in a normal irrigated soil is very limited and can be neglected, especially in old or mature soils. In recent soils, the contribution depends on the original make up, stage of development, climate,and management. Although the process is a slow one, certain minerals, when present in excess of the very low level concentrations tolerable (about 5 ppm for boron and 0.1 ppm for lithium), become toxic to plants.

Chemical fertilizers are being more and more applied to the soil but not necessarily affecting soil salinization. Nitrogenous fertilizers are easily leached in drainage water or volatilized in the gaseous form. The contribution from manures to the salt content of the soils can be quite high. Amounts equivalent to 1 to 2 tons of salts per hectare could be added when unleached farm manures, from dairy and feedlots, containing 10% total soluble salts are applied at the rate usually recommended for an adequate supply of nutrients (Rauschkolb, 1971). Amendments, mainly gypsum, are of limited solubility and there is no risk of salinity developing when they are applied to the soil.

Crop residues incorporated into the soil add very little to its salt content. Although the amount of residues from various field and row crops may vary from 4 to 12 tons (fresh weight) per hectare (California State Dept. of Public Health, 1968), the amount of soluble salts returned to the soil will be very small since the bulk is moisture, organic hydrocarbons and nitrogenous compounds.

Interpretation and Limitations of the Salt Balance

The comprehensive form of the salt balance can be presented simply by introducing certain assumptions to account for the relatively small contribution or balancing effects of the M, F, T, W components and precipitation in arid regions. Moreover, the artesian, seepage and surface run-off waters where they are not of common occurrence can be considered of minor importance. The absence of deep percolation, as a result of an impermeable aquiclude that intercepts drainage water, or insufficiency of water application to yield deep outflow, will further simplify the presentation of the salt balance to:

$$IC_i + GC_g - DC_c = \pm \Delta S$$

This form can further be reduced by assuming a steady state, $S = 0$, and no contribution from the groundwater, so that the salt balance in its simplest form is the difference between salt outputs and salt inputs;

$$SB = DC_d - IC_i$$

The relation between salt inputs and outputs can also be presented by the salt balance index, SBI = output of salt/input of salt, or simply DC_d/IC_i, for the total salt concentration or for a given ion in the effluent to its corresponding amount in the influent.

For prognostic investigations, negative, positive,and no changes of SB may indicate trends towards salinization, desalinization,and equilibrium conditions, respectively. Realizing the usefulness of the salt balance data, one should also be aware of their limitations and the need for careful interpretation. A negative change may not be to the extent that crops are suffering, a positive one does not necessarily mean a reduction of the salt content to a safe level, and a zero change can occur while the salt content is still high. Furthermore, changes in between monitoring dates may not be exactly known. Not only that, but in studies on large areas, smaller units showing different trends could exist.

Considering the above limitations and those arising from the use of simplified forms or inaccurate estimates, it is important for prognostic purposes to analyze and use the salt balance investigations in terms of their indicative trends.

SODICATION

Sodication

Sodication in the context of this paper is analogous to the other widely used terms: alkalization and solonetz formation, referring to the processes whereby the exchangeable sodium content of a soil is increased to the extent that it causes deterioration of the soil structure, reduction of soil permeability, and specific harmful effects on plants. These physical and nutritional effects and related parameters, modifying or affecting them, are of direct importance to prognosis and monitoring of sodic soils and therefore merit some elaboration.

Physical Effects of Exchangeable Sodium

Swelling of clay minerals upon wetting and their dispersion account for the deterioration of the soil structure and a decrease in permeability. This is enhanced in the presence of high exchangeable sodium, low salt content and swelling clay minerals. Soil parameters such as infiltration, diffusivity, and hydraulic conductivity are materially reduced by increasing ESP, especially above 15 (Massoud and El-Zeftawi, 1973). However, the magnitude of the effect of exchangeable sodium on soil permeability varies with the salt concentration (Quirk and Schofield, 1955). The work of McNeal and Coleman (1966) indicates the ability of the major agricultural soils (high in 2:1 layer silicates but moderate in montmorillonite) to tolerate ESP values of 15 or greater before serious reduction in K occurs providing the salt concentration of the percolating water exceeds 3 meq/1. A rather pronounced hydraulic conductivity decrease in the ESP range of 25 to 35 at salt concentrations of 3 to 50 meq/1 was observed. The type of clay minerals has to be considered in evaluating the level of ESP affecting K, as montmorillonite will be affected at a level lower than illite or kaolinite (Yaron and Thomas, 1968).

Nutritional Effects of Exchangeable Sodium

High sodium content in the soil solution does not only contribute to the total salt concentration and high osmotic potential but Na absorbed by plants might accumulate in toxic quantities or cause imbalanced uptake of nutrients. Bernstein (1974) reported on the nutritional effects of exchangeable sodium and how the ESP level causing sodium toxicity varies with the crop sensitivity and salt concentration. Sensitive crops such as deciduous fruits, citrus, and avocado are affected at low ESP level, about 5, which is below levels normally associated with structural deterioration, while soluble sodium as low as 5 to 10 meq/l of the saturation extract will cause nutritional problems to these crops. The ESP level tolerable by most crops can reach as high as 35 in a sodic soil if a favorable structure can be maintained (Bernstein and Pearson, 1956; Pearson and Bernstein, 1958). Similarly, in the presence of salts, as in saline-sodic soils, the plants can withstand a relatively high ESP, more than in non-saline sodic ones because of the presence of sufficient Ca and Mg to restore any nutritional imbalances.

The characteristics of the sodic soils just mentioned necessitate that in the prognostic and monitoring studies, factors other than ESP should be considered, including structure, permeability (K), and soluble salt content.

MANAGEMENT PRACTICES

Agronomic and Soil Management Practices

Among the various agronomic and soil management practices salt leaching, crop selection and rotations, land levelling and fallowing are considered as factors with a long term effect on soil salinization and deserve some weight in prognostic investigations (Massoud, 1976). Other factors including tillage, mulching, planting site and application of fertilizers, manures and amendments, although they are important, have but a short term effect that can be corrected with less difficulty.

Leaching for Salinity and Sodicity Control

Application of excess water, above that needed for ET, to leach salt accumulated from previous watering is a healthy exercise to control salinity. Realizing the dual effect of leaching requirement applications, namely soil desalinization and increasing the salt load of the groundwater, the recent trend to minimize the leaching requirement (Bernstein and Francois, 1973; Rhoades, 1974) has to be carefully considered. Efficient management of irrigation and drainage systems to keep the salts pushed downwards and to minimize the upward water flux is essential. The leaching requirement for sodicity control (LR_{SAR}) has been demonstrated by Bower et al. (1968) and Rhoades and Merrill (1976) to be of value in reducing ESP. However, the concept as introduced by Rhoades (1968) needs further publicity and establishment of the recommended LR_{SAR}.

Crop Selection and Rotation

Plants differ in their tolerance to salinity and sodicity; moreover, they vary in their water requirements, season of growth, rooting depth and moisture extraction patterns, and cultural requirements. Consequently, in the absence of proper water and soil management practices salinity of the soil may be affected differently under various crop rotations. Crops such as rice, berseem, and those requiring frequent irrigation reduce salinity effectively, especially where drainage is adequate.

For prognosis, an advance knowledge of the expected salt balance under various crop rotations is very important, as it is for monitoring salinity and sodicity after each crop or at least once in a given crop rotation.

Land Leveling and Tillage

Changes in the microrelief in the order of less than 30 cm result in increasing salt content on the raised spots and better leaching in the dips. Repeated land shaping before cropping would help to correct these changes in elevation. Land leveling that results in the formation of shallow profiles or exposure of an impervious layer close to the surface enhances salinization and is not easy to correct. Since this operation is executed at an early stage in new surface irrigated projects, it should be carefully evaluated as a possible cause of secondary salinization.

Tillage is another mechanical operation that is usually carried out for seed bed preparation and soil permeability improvement but if improperly executed might form a plow layer or turn a salty layer and bring it closer to the surface. For prognosis and monitoring purposes the depth, reversibility and compaction of the plow layer should be investigated.

Fallowing and Mulching

The relation of fallowing to soil salinization should be evaluated in the light of the previous discussion on shallow groundwater and evapotranspiration. The danger of fallowing is high where a shallow water table exists since exaporation rates of about 8, 3 and 1 mm/day would occur from the dry surface of a fine sandy loam when the water table is kept at 90, 120 and 180 cm, respectively.

Mulching to reduce evaporation losses will also decrease the opportunity for soil salinization. Management practices beside mulching, such as avoiding water circulation in fallow areas or separating fallow zones from cropped ones, should also be assessed.

Application of Manures, Fertilizers, and Amendments

Manures, beside the favorable effect they have on the physical and nutritional properties of the soil, may add considerable amounts of salts, as previously discussed. Manures should be analyzed for their salt content and the accumulative effect. Fertilizers when applied properly as to dose and placement will not affect salinization; however, the chemical composition, solubility, rate of release, and method of placement, especially in the early stages of plant growth, have to be considered if they are applied to salt affected soils.

Amendments are added mainly to sodic soils as a corrective measure to reduce ESP and improve permeability and, therefore, should be given favorable consideration.

Planting Site and Techniques

Salinity effects, especially during germination and seedling stage, are modified by planting site and technique. Planting on top of a ridge in a saline soil gives a poor stand, while in sodic soils it would help seedlings to withstand waterlogging. A greater requirement of seeds, fewer seedlings emerging, and a delay in emergence can be signs of salinity or sodicity hazards, if other conditions are normal. Keeping records of these agronomic observations would help in salinity prognosis.

METHODS OF PROGNOSIS AND MONITORING

Monitoring of the salinity and sodicity at the time of sampling can be considered also as a useful tool for predictive investigations when the monitored data are examined in a chronosequence. It would be much better if the information collected in the early stages of planning and designing of a project could be used to predict in advance the possibility of soil salinization or sodication. Various investigations and techniques can be used for prognosis and monitoring. Some of the methods are complementary to each other and may vary in time scale, input requirements, and reliability; moreover, they are also used for purposes other than those we are concerned with in this paper and, therefore, will have to be adapted to suit prognosis and monitoring of salinity and sodicity. A brief account of these methods and how they can be used for this specific purpose is given here.

Soil and Hydrological Surveys

The standard soil survey is an important and useful tool when used for delineating the various kinds of soils and making predictions of their behavior under different management. In this regard the survey has to be guided by certain basic principles.

1. Prediction Principle: This principle of prediction should be acknowledged by the planners and applied in practice by the surveyors, particularly when selecting new lands for irrigation (Maletic and Hutchings, 1967). During the exploratory studies, soils must not only be delineated, as they are now, but also predictions must be included as to how they will change upon irrigation, drainage, and other consequent changes in the salt balance (Flach, 1976). The prediction principle should also be applied to water quality and use.

2. Permanent-Changeable Factors Principle: This principle recognizes the changes in land arising from water and land development and requires the identification of characteristics that will remain without major changes, also those which will be significantly altered (Peters, 1976).

3. Deeper and Wider Boundaries Principle: It may be that factors effecting soil salinization and sodication are not necessarily present within the normal depth of investigation or of the root zone and the limited boundaries of the project at the time of investigation, but the soil becomes salt affected later on. Further studies may reveal the causes of this degradation are embedded in deeper strata or imported from adjacent areas. This principle, therefore, stresses the necessity of looking into the soil and water properties of the deeper substrata and considering the characteristics of the areas outside the project boundary and their future development.

4. The Multidisciplinary Approach Principle: Since numerous factors belonging to the fields of soils, meteorology, geology, geochemistry, geophysics, hydrogeology, hydrology, human activities, topography, and economy influence the salt affected soils (Szabolcs et al., 1976), the multidisciplinary approach principle implies that full advantage be made of information or surveys developed for the area and surroundings. Similarly, experts in the above subject matters should be consulted, especially in the preparatory phase of the project to advise on the type of surveys needed.

Example of Surveys with an Effective Goundwater Regime

Salty groundwater plays a significant role in soil salinization and sodication especially in lowland basins, depressions, or deltas of restricted normal drainage or no outlets and where ET exceeds precipitation, as in the Hungarian Plain. Therefore, the prognosis procedure developed by Hungarian scientists (Szabolcs et al., 1969) could be of use if adapted to suit similar conditions.

The prognosis surveys are carried out in two stages:

1. reconnaissance type (1:100,000 up to 1:500,000) to prepare the following maps: genetic soil map, map of the average depth to the groundwater level, map of the minimum depth of the water table, map of the average salt concentration in the groundwater, and a map of the chemical composition of the groundwater.

2. detailed type (1:25,000) to prepare the following maps: soil types and subtypes, soil texture and water-soil characteristics, salinity status, groundwater conditions, and depth to the water table.

Data collected from these investigations are needed for the calculation of the critical depth to water table and the forecasting of the rate of salt accumulation at different depth to groundwater. Varallyay (1974) has contributed to the improvement of the procedures and calculations. It is now possible through computer programming and availability of the K- ρ relationship and suction profiles to determine the rate of capillary rise and salt accumulation in uniform as well as layered soils.

Example of Monitoring with Efficient Water Management Practices

With efficient water management practices it is possible to control irrigation and drainage systems and where records are kept on the volume and salt content of the influent and effluent waters, respectively delivered to and discharged from the area, the salt balance as a prognostic method can be applied. The irrigated area of the Imperial Valley, California, provides a good site for demonstrating this approach. The diversion of irrigation water from Colorado River into the All American Canal and its three branches, and the discharge of most surface drainage water into the Alamo and New Rivers and Salton Sea make it possible to monitor easily the quantities and qualities of most influent and effluent waters, excluding groundwater. Moreover, the topographic and geologic features of the valley provide favorable circumstances for foreign groundwater to be discharged into the area and its main drainage collectors. This means that not only the surface drainage but also the groundwater discharges and qualities should be monitored and evaluated.

Intensive monitoring of the water table depth, quantities of the influent water and those leaving the valley, the amount and composition of the salt load is being undertaken regularly by the Imperial Irrigation District. Kaddah and Rhoades (1976) applied the salt balance to evaluate the monitored data and assess soil salinity trends using the monitored and estimated quantities of the influent and effluent waters: irrigation water, precipitation, tailwater, intercepted root zone percolation water, soil water in the root zone, groundwater below the root zone, seepage from canal, sewage effluent and canal spillage, and consumptive use.

They further were able to estimate, based on simplified assumptions and the use of Cl in the effluent water as a tracer, the various components of the effluent water from the Imperial Valley as 55, 35, and 10 percent from groundwater, root zone drainage, and tailwater, respectively.

Field Investigations and Laboratory Analyses

Field investigations and laboratory analyses of the parameters affecting salinization, sodication, and the reverse processes are diagnostic tools but the results are used for recommending remedial measures and when evaluated in a chronosequence or with a predictive objective they become useful prognostic methods. It is essential to have enough information on this wide range of parameters as background or reference material that will help to explain present and future trends. While monitoring is usually concerned with the most effective factors and changing properties, the basic field investigations and laboratory analyses should cover all those soil, soil-water, water, climate, crop, and management parameters involved in salt and water movement, redistribution, and change in composition or content.

Priority, Frequency, and Accuracy

Once the results from the basic investigations and analyses are known, there is no need to over-test, and a priority should be set for every circumstance according to the potential source and mechanism affecting the soil. For example, potential salinization due to salty irrigation water would emphasize testing of: quality and quantity of irrigation water, leaching fraction, vertical salt distribution in the root zone, soil permeability, and texture.

The frequency of sampling or monitoring of a given parameter varies with the magnitude and extent of its vertical and horizontal changes with time. In this respect the following parameters might require more frequent testing than the others:

1. Soil: salinity, salt composition, ESP, pH;
2. Soil-water: depth to water table, infiltration rate, and hydraulic conductivity;
3. Water: salinity and salt composition, quantity of influent and effluent waters;
4. Climate: evaporation rate, temperature, sunshine; and
5. Crops and Management: crop performance and yield, leaching fraction.

Generally speaking, in a newly developed area a more frequent monitoring is recommended. Also monitoring for salinity means testing at a closer interval than for sodicity.

The reliability of the monitored data depends, in the first place, on the accuracy of sampling, and measurements or analyses. Therefore, selection of the site, obtaining representative samples taken from an optimum number of samples and locations. and following the right sampling and analysis procedures can assure the accuracy of the monitored data (Elgabaly, 1971). Application of statistical methods to sampling (Sayegh et al., 1958) as well as to data evaluation (Nightingale, 1970; 1974) in the field of soil and water salinity are being used to improve the reliability of the data and their presentation in a concise meaningful way.

Laboratory and Field Characterization of Salinity and Sodicity

The quantitative chemical assessment of salinity and sodicity is mostly determined on disturbed samples in the laboratory following standard procedures (USSL Staff, 1954; Black et al. 1965; Darab, 1976). Needless to say, only the data obtained by the same method, especially for ESP, can be compared. It is therefore advisable to correlate the salinity results obtained from methods other than the electrical conductivity of the saturation extract with those from the latter, mostly used as a base for interpretation.

Due to the tedious work required for sampling and the expensive time and cost involved, if repeated analyses are needed, in situ measurement of soil salinity has been suggested by Shea and Luthin (1961), Enfield and Evans (1969), Rhoades and Ingvalson (1971) and Oster and Willardson (1971). The 4-electrode soil conductivity technique has been successfully used and has many applications for measuring, mapping and monitoring soil salinity and sodicity, detecting the presence of a shallow water table, and estimating leaching fraction (Halvorson and Rhoades, 1974; Rhoades, 1976). Detailed information on salinity and sodicity distribution with depth can be obtained with the "EC-probe" recently developed by Rhoades and van Schilfgaarde (in prep).

Use of Satellite Imagery

Application of satellite imagery to agriculture covers many fields; so far the application of the Earth Resources Technology Satellite (ERTS; LANDSAT) to assessment of soil salinity and sodicity problems is still limited and mostly used for experimental investigations. The technique, if proved to be applicable to diagnosis and monitoring of salt affected soils, will cause a break-through in the time scale and extent of coverage and will, therefore, become a very useful prognostic tool. It would be possible then to monitor in an eighteen day cycle (with one frame 9.5 x 9.5 inches) an area of about 5.6 million ha and save, to a great extent, the tedious work of the field soil survey.

Field Studies

The feasibility of using ERTS imagery to appraise soil salinity and sodicity in the Indus Plain in Pakistan, through interpreting the imagery in the light of available information in areas of known types of salt affected soils, has been demonstrated and a fair correlation obtained (Rafiq, 1976). In a more comprehensive study carried out by the Department of Soils and Plant Nutrition, U.C. Davis (Huntington, 1973) to investigate the effectiveness of ERTS-1 imagery to identify and delineate salt affected lands within California, the results are encouraging in some aspects, such as identifying sodic or saline barren soils. However, no consistent detection of reduced infrared reflectance from fields of the same irrigated crop plants growing in normal or salt affected soils could be made. This limited resolution of the infrared color composites will pose no problem if Skylab or other satellites with longer focal length sensors are used. This is indicated from the investigations by Wiegand et al., (1976) who were able to differentiate partially between primarily undisturbed saline and non-saline range lands using Skylab imagery. Moreover, Skylab and LANDSAT-1 MSS data were significantly correlated to the electrical conductivity readings.

Limitations

Optimum techniques still need to be developed to detect various levels of soil salinity and sodicity, to differentiate between the forms of the salt composition and their vertical distribution. The technique is still unable to determine the salt content and composition of the various water sources contributing to the salt balance. Moreover, there is a need for a screening system which will separate the causes of various plant symptoms giving similar reflectance and show the difference between barren and fallow soils of salt affected or normal soils when they are plowed.

Modelling

Mathematical modelling, whereby scientists try to simulate actual field conditions and produce clarifying or forecasted answers, should be considered as an applied methodology and not as an end in itself. In the field of salt affected soils, modelling is mainly concerned with the movement of salt and water in the soil and the results are verified by controlled experimental work in soil columns, lysimeters, or, to a lesser extent, under field conditions. Since numerous natural and man-made factors are involved in salinization, sodication, and the reverse processes their inclusion as integrated inputs is a basic requirement for reliable model programming. Moreover, the dynamic nature of these factors, mainly the soil-water regime, plant growth, evaporativity, and management should be considered. In fact, one of the main shortcomings of modelling is the difficulty of quantifying in an integrated approach the specific parameters and the various processes in the soil-plant-atmosphere continuum.

Although a comprehensive model that can predict the salt regime in the root zone or a given soil body under various circumstances is still lacking and needed, several models each describing a specific set of inputs are available. They provide useful information and correlate fairly well with actual or expected conditions. The models developed by Terkeltoub and Babcock (1971); Obukhov (1974); Varallyay (1974); Childs and Hanks (1975); Oster and Rhoades (1975); Rhoades and Merrill (1976); and Hillel et al., (1976) are mentioned as examples.

SUMMARY

The development of a standardized methodology for prognosis and monitoring of salinity and sodicity for application throughout the world may not be easily achieved or appropriate practically where conditions vary from one location to another as is the case in salt affected soils. Moreover, there is usually an element of risk in attempting to transfer the procedures and to over-generalize the use of an established standard methodology without giving enough consideration to local changes or needs. The common tendency to adopt rather than to adapt a methodology quite often gives misleading results and it would be more fruitful and, in this case essential, to go through the rigors of applying the principles. Therefore, knowledge of the basic principles discussed in this paper is an indispensible requirement for the development of local procedures or the adoption of an established methodology.

REFERENCES

Bernstein, L. 1974. Crop growth and salinity. In J. van Schilfgaarde (ed.) Drainage for Agriculture. Agronomy 17., Amer. Soc. Agron., Madison, Wisconsin.

Bernstein, L., and L. E. Francois. 1973. Leaching requirement studies: Sensitivity of alfalfa to salinity of irrigation and drainage waters. Soil. Sci. Soc. Amer. Proc. 37:931-943.

Bernstein, L., and L. E. Francois. 1975. Effects of frequency of sprinkling with saline waters compared with daily drip irrigation. Agron. J. 67:185-190.

Bernstein, L., and G. A. Pearson. 1956. Influence of exchangeable sodium on the yield and chemical composition of plants. I. Green beans, garden beets, clover and alfalfa. Soil Sci. 82:247-258.

Black, C. A., D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark, editors. 1965. Methods of Soil Analysis. Agronomy 9. Amer. Soc. Agron. Madison, Wisconsin.

Bower, C. A., G. Ogata, and J. M. Tucker. 1968. Sodium hazard of irrigation waters as influenced by leaching fraction and by precipitation or solution of calcium carbonate. Soil Sci. 106:29-34.

California State Department of Public Health. 1968. Status of solid waste management, Interim Report.

Childs, S. W., and R. J. Hanks. 1975. Model of salinity effects on crop growth. Soil Sci. Soc. Amer. Proc. 39:617-632.

Christiansen, J. E., and J. R. Davis. 1967. Sprinkler irrigation systems. In Hagan, R. M., H. R. Haise, and I. W. Edminster (eds.) Irrigation of Agricultural Lands. Agronomy 11, Amer. Soc. Agron., Madison, Wisconsin.

Darab, K. 1976. Laboratory analyses of soils related to the prognosis and monitoring of salinity and alkalinity. Soil Bulletin 31, FAO, Rome.

Elgabaly, M. M. 1971. Problems of sampling, analyzing and mapping of salt affected soils. Irrigation and Drainage Paper 7, FAO, Rome.

Elgabaly, M. M., and N. M. Naguib. 1965. Effect of depth and salt concentration of groundwater on salinization of soil. Agrokemia Es Talajtan 14, Budapest.

Enfield, C. G., and D. D. Evans. 1969. Conductivity instrumentation for in situ measurement of soil salinity. Soil Sci. Soc. Amer. Proc. 33:787-789.

FAO. 1976. Prognosis of salinity and alkalinity. Soils Bulletin 31, FAO, Rome.

FAO/UNESCO. 1973. Irrigation, Drainage and Salinity, an international source book (Kovda, V.A., C. van den Berg, and R. M. Hagan (eds.), Hutchinson/FAO/UNESCO).

Flach, K. W. 1976. Soils and hydrologic surveys. Soils Bulletin 31, FAO, Rome.

Gardner, W. R. 1958. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci. 85:228-232.

Gardner, W. R., and M. Fireman. 1958. Laboratory studies of evaporation from soil columns in the presence of a water table. Soil Sci. 85:244-249.

Halvorson, A. D., and J. D. Rhoades. 1974. Assessing soil salinity and identifying potential saline-seep areas with field soil resistance measurements. Soil Sci. Soc. Amer. Proc. 38:576-581.

Hillel, D., H. Talpaz, and H. van Keulen. 1976. A macroscopic-scale model of water uptake by a nonuniform root system and of water and salt movement in the soil profile. Soil Sci. 121:242-245.

Huntington, G. The use of ERTS-1 data in identification, classification and mapping of salt affected soils in California. The Department of Soils and Plant Nutrition, Univ. of California, Davis.

Keller, J. 1965. Effects of irrigation method on water conservation. J. Irrigation and Drainage. Div. ASCE 91.

Khaddah, M. T., and J. D. Rhoades. 1976. Salt and water balance in Imperial Valley, California. Soil Sci. Soc. Amer. Jour. 40:93-100.

Kovda, V. A. 1971. Origin of saline soils and their regime. Vol. 1, translated from Russian (Prasolov, L. I., ed.), USDA, Washington, D.C.

Kovda, V. A. 1973. USSR nomenclature and classification of saline soils. In Kovda, V. A., C. van den Berg, and R. M. Hagan (eds.) Irrigation, Drainage and Salinity, an international source book. Hutchinson/FAO/UNESCO.

Kraatz, D. B. 1971. Irrigation canal lining. Irrigation and Drainage Paper 2, FAO, Rome.

Luthin, J. 1957. Drainage of irrigated lands. In J. Luthin (ed.) Drainage of Agricultural Lands. Agronomy 7. Amer. Soc. Agron., Madison, Wisconsin.

Maletic, J. T., and T. B. Hutchings. 1967. Selection and classification of irrigable land. In Hagan, R. M., H. R. Haise, and I. W. Edminster (eds.) Irrigation of Agricultural Lands. Agronomy 11, Amer. Soc. Agron., Madison, Wisconsin.

Manor, S. 1974. Prediction of the zone of water uptake by plants in the presence of a water table. Ph.D. Thesis. Colorado State University, Ft. Collins.

Massoud, F. I. 1964. Analysis of the flow of water from the water table in presense of plant roots. Ph.D. Thesis. University of California, Davis.

Massoud, F. I. 1974. Salinity and alkalinity as soil degradation hazard. FAO/UNEP Expert Consultation on Soil Degradation (AGL:SD/74/10), FAO, Rome.

Massoud, F. I. 1976. Soil management and agronomic practices. Soils Bulletin 31, FAO, Rome.

Massoud, F. I., and A. A. El Zeftawi. 1973. The effect of exchangeable sodium on infiltration and diffusivity of water through soil. Proc. of the Int. Symp. on Salt Affected Soils, Cairo, 1972.

McNeal, B. L., and N. T. Coleman. 1966. Effect of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Amer. Proc. 30:308-312.

Nightingale, H. I. 1970. Statistical evaluation of salinity and nitrate content and trends beneath urban and agricultural areas - Fresno, California. Ground Water 8:22-28.

Nightingale, H. I. 1974. Soil and ground water salinization beneath diversified irrigated agriculture. Soil Sci. 118:365-373.

Nugteren, J. 1973. Effects of irrigation and drainage. Publication 16, Vol. 2, International Institute for Land Reclamation and Improvement (ILRI), Wageningen.

Obukhov, A. D. 1974. Predicting the dynamics of soil desalinization in a rice rotation. Soviet Soil Sci. 6:598-604.

Oster, J. D., and J. D. Rhoades. 1975. Calculated drainage water compositions and salt burdens resulting from irrigation with river waters in the Western United States. J. Environ. Qual. 4:73-79.

Oster, J. D., and L. S. Willardson. 1971. Reliability of salinity sensors for the management of soil salinity. Agron. J. 63:695-698.

Pearson, George A., and Leon Bernstein. 1958. Influence of exchangeable sodium on yield and chemical composition of plants. II. Wheat, barley oats, rice, tall fescue, and tall wheatgrass. Soil Sci. 86: 254-261.

Peters, W. B. 1976. Economic land classification for the prevention and reclamation of salt affected soils. Soils Bulletin 31, FAO, Rome.

Quirk, J. P., and R. K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci. 6:163-178.

Raats, P. A. C., and W. R. Gardner. 1974. Movement of water in the unsaturated zone near a water table. In J. van Schilfgaarde (ed.) Drainage for Agriculture. Agronomy 17. Amer. Soc. Agron., Madison, Wisconsin.

Rafiq, M. 1976. Use of satellite imagery for salinity appraisal in the Indus Plain. Soils Bulletin 31, FAO, Rome.

Rauschkolb, R. 1971. Land Degradation. Soils Bulletin 13, FAO, Rome.

Reeve, R. C., A. F. Pillsbury, and L. V. Wilcox. 1955. Reclamation of a saline and high boron soil in Coachella Valley of California. Hilgardia 24:69-91.

Rhoades, J. D. 1968. Leaching requirement for exchangeable - sodium control. Soil Sci. Soc. Amer. Proc. 32:652-656.

Rhoades, J. D. 1974. Drainage for salinity control. In J. van Schilfgaarde (ed.) Drainage for Agriculture. Agronomy 17, Amer. Soc. Agron., Madison, Wisconsin.

Rhoades, J. D. 1976. Measuring, mapping and monitoring field salinity and water table depths with soil resistance measurements. Soils Bulletin 31, FAO, Rome.

Rhoades, J. D., and R. D. Ingvalson. 1971. Determining salinity in field soils with soil resistance measurements. Soil Sci. Soc. Amer. Proc. 35:54-60.

Rhoades, J. D., and S. C. Merrill. 1976. Assessing the suitability of water for irrigation: theoretical and empirical approaches. Soil Bulletin 31, FAO, Rome.

Sayegh, A. H., L. A. Alban, and R. G. Petersen. 1958. A sampling study in a saline and alkali area. Soil Sci. Soc. Amer. Proc. 22;252-254.

Scofield, C. S. 1940. Salt balance in irrigated areas. J. Agr. Res. 61:17-39.

Shea, P. F., and J. N. Luthin. 1961. An investigation of the use of four-electrode probes for measuring soil salinity in situ. Soil Sci. 92: 331-339.

Szabolcs, I. (ed.). 1971. European solonetz soils and their reclamation. Akademiai Kiado, Budapest.

Szabolcs, I. 1976. Present and potential salt affected soils - An introduction. Soils Bulletin 31, FAO, Rome.

Szabolcs, I., K. Darab, and G. Varallyay. 1969. Methods of predicting salinization and alkalinization processes due to irrigation on the Hungarian Plain. Agrokemia Es Talajtan 18, Budapest.

Szabolcs, I., G. Varallyay, and K. Darab. 1976. Soil and hydrologic surveys for the prognosis and monitoring of salinity and alkalinity. Soils Bulletin 31, FAO, Rome.

Terkeltoub, R. W., and K. L. Babcock. 1971. A simple method for predicting salt movement through soil. Soil Sci. 111:411-414.

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S. Dept. Agriculture, Handbook 60.

Van der Molen, W. H. 1976. Factors to be considered for prognosis - Natural factors. Soils Bulletin 31, FAO, Rome.

Van Schilfgaarde, J. 1976. Water management and salinity. Soils Bulletin 31, FAO, Rome.

Varallyay, G. 1974. Unsaturated flow studies in layered soil profiles. Agrokemia Es Talajtan 23, Budapest.

Wiegand, C. L., A. J. Richardson, H. W. Gausman, R. Leamer, and A. H. Gerbermann. 1976. Soil salinity detection. NASA Earth Resources Survey Program, U.S. Dept. of Commerce, NTISUB/B/093 - 76/014.

Wind, G. P. 1955. A field experiment concerning capillary rise of moisture in a heavy clay soil. Neth. J. Agri. Sci. 3.

Yaron, B., and G. W. Thomas. 1968. Soil hydraulic conductivity as affected by sodic water. Water Resources Research 4:545-552.

SALINE WATER CLASSIFICATION IN IRAN
BY RATIONAL METHODS

A. M. Massoumi[1]

INTRODUCTION

Different investigators have shown the electrical conductivity is insufficient as the criterion for evaluating irrigation water quality. Durand in Algeria, Darab in Hungary, and Shalhevet (1973) in Israel have noted that a high percentage of the waters presently used successfuly for irrigation are not of good quality if they are evaluated by the U. S. Salinity Laboratory (1954) method. The recommended upper limit of irrigation water salinity, according to U. S. Salinity Laboratory criteria, is 2250 micromhos/cm, under ordinary conditions. Several suggestions have been made for increasing this limit, in view of the widespread use of more saline waters for irrigation.

In countries like Iran, with an arid and semi-arid climate, the correct evaluation of irrigation water is very important for land use planning in new irrigated areas. Application of the U. S. Salinity Laboratory criteria has not been satisfactory for Iranian conditions. The objective of this paper is to present a different method of water quality evaluation, based upon salt tolerance of plants, soil permeability, and irrigation efficiency. The method is referred to as the "rational" method.

PRINCIPLE OF METHOD

The principle of the rational method is to take into consideration four factors as follows:

- Salinity of the water
- Resistance of plants to salinity
- Texture of the soil to be irrigated
- Quantity of water applied to soil, or irrigation efficiency

From these factors, based on salt and water balance in the soil, it is possible to determine an equation for the evaluation of the irrigation water. According to Van der Molen (1967), the moisture and salt balance of the root zone may be written as follows:

$$I + N + G = ET + P + \Delta V \qquad (1)$$

$$I\ Ci + Gcg = P.cp + \Delta Z \qquad (2)$$

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where:

I = volume of irrigation water
N = volume of rainfall
G = volume of capillary water entering root zone from below
ET = evapotranspiration
P = volume of deep percolation water
Ci = salinity of irrigation
Gcg = salinity of capillary water
Pcp = salinity of deep percolation water
ΔV = change in moisture content of soil
ΔZ = change in salt content of soil

When the salinity of the soil is controlled so that during the year the increase of salt is equal to the quantity leached, the ΔZ becomes zero. When there is equilibrium the concentration of salt in the capillary (Cg) and percolation (Cp) waters is equal, or

$$Cg = Cp \qquad (3)$$

However, usually, the CP is less than the salt concentration of the soil moisture (Csm) at field capacity, and in the case of saline water for irrigation, the concentration of salts in the percolation water may be obtained from:

$$Cp = KCsm + (1-K)\ Ci \qquad (4)$$

K is a soil parameter (permeability) which depends on texture. Combining equations 1, 2, and 4 we obtain

$$P - G = \frac{(ET-N)\ Ci}{K(Csm-Ci)} \qquad (5)$$

Assuming that the EC of the soil solution is proportional to its salt concentration, the above computation may be carried out directly with EC substituted for C. For soils of moderate texture the EC of the soil solution at field capacity (ECex) is approximately twice the EC at saturation. So we can write

$$P - G = \frac{(ET-N)\ ECi}{K(2ECex - ECi)} \qquad (6)$$

and the total quantity of irrigation water should be

$$I = (ET-N) = \frac{ECi}{K(2ECex - ECi)} + 1 \qquad (7)$$

Assuming that the irrigation efficiency (R) in the field is equal to

$$R = \frac{ET-N}{I} \qquad (8)$$

and substituting R into the above equation, we obtain the following equation:

$$ECI = \frac{2KECex\ (1-R)}{K+R\ -\ K\ R} \qquad (9)$$

From the above equation, we can see that, for a given soil and plant, the limit of salinity of water to be used for irrigation varies only with R (irrigation efficiency). In this case we have proposed (3) to evaluate the suitability of water from R as follows:

R %	Suitability classes
>80	I
80-60	II
60-40	III
40-20	IV
<20	V

It is clear that with a high irrigation efficiency (low leaching fraction), the soil does not need to be drained, whereas with a low efficiency (high leaching fraction) the soil must be drained. This is economically important.

APPLICATION OF THE METHOD

We have applied this method to 396 rivers of Iran. The rivers of Iran, particularly those of the south traverse tertiary (miocene) formation; the salt concentration of these rivers increases greatly as they approach the sea.

We have selected four groups of plants, with varying resistance to salinity as follows, with salinity expressed as the electrical conductivity of the soil solution at field capacity:

Group	ECex
1	16 mmhos/cm
2	12 mmhos/cm
3	8 mmhos/cm
4	4 mmhos/cm

and three types of soil texture. Soil texture is an indication of soil permeability (K). K is 0.3 for fine textured soil, 0.5 for medium textures, and 0.7 for coarse texture. The EC of several samples of each of the 396 rivers have been measured, and the mean calculated.

From equation 9 we have calculated the irrigation efficiency necessary for irrigation of the four groups of plants in the three soils, by which the salinity of soils is controlled. We have classified the 396 rivers according to suitability. The percentage of waters in each class is shown in Table 2 and Figures 1 to 4.

To compare the results from this method and the U.S.S.L. methods(s) we have calculated the distribution of suitability of waters by U.S.S.L. method (Table 3).

RESULTS AND DISCUSSION

Irrigation efficiency could vary from zero to 100 percent. In that case, the salinity of water, as it can be calculated from equation 2, varies from zero to ECex, or:

as R goes to 0, ECi goes to 2 ECex and as R goes to 1, ECi goes to 0.

If we calculate the limit of Ec of water for the above groups of plants and soils with different irrigation efficiency we obtain the results shown in Table 2.

Table 1: Distribution of suitability (in percentage), using the rational method, of river waters of Iran.

ECex	R K	100	80	60	40	20
16	0.3	88.04	7.18	2.39	2.39	-
	0.5	92.82	3.83	2.39	0.96	-
	0.7	95.29	1.91	2.87	-	-
12	0.3	82.78	10.53	3.35	2.39	0.96
	0.5	91.39	4.31	0.26	3.35	-
	0.7	92.82	3.83	1.44	1.91	-
8	0.3	77.03	14.35	3.35	2.39	2.87
	0.5	86.12	7.18	3.35	1.44	1.91
	0.7	90.91	3.83	1.91	1.44	1.91
4	0.3	46.89	31.10	12.92	3.83	5.26
	0.5	66.99	16.27	8.13	3.83	4.78
	0.7	75.60	10.53	7.66	1.91	4.31

FIG 1 DISTRIBUTION OF SUITABILITY FOR IRRIGATION, USING RATIONAL METHOD, (IN PERCENTAGE) OF RIVER WATERS IN IRAN

(ECex = 4)

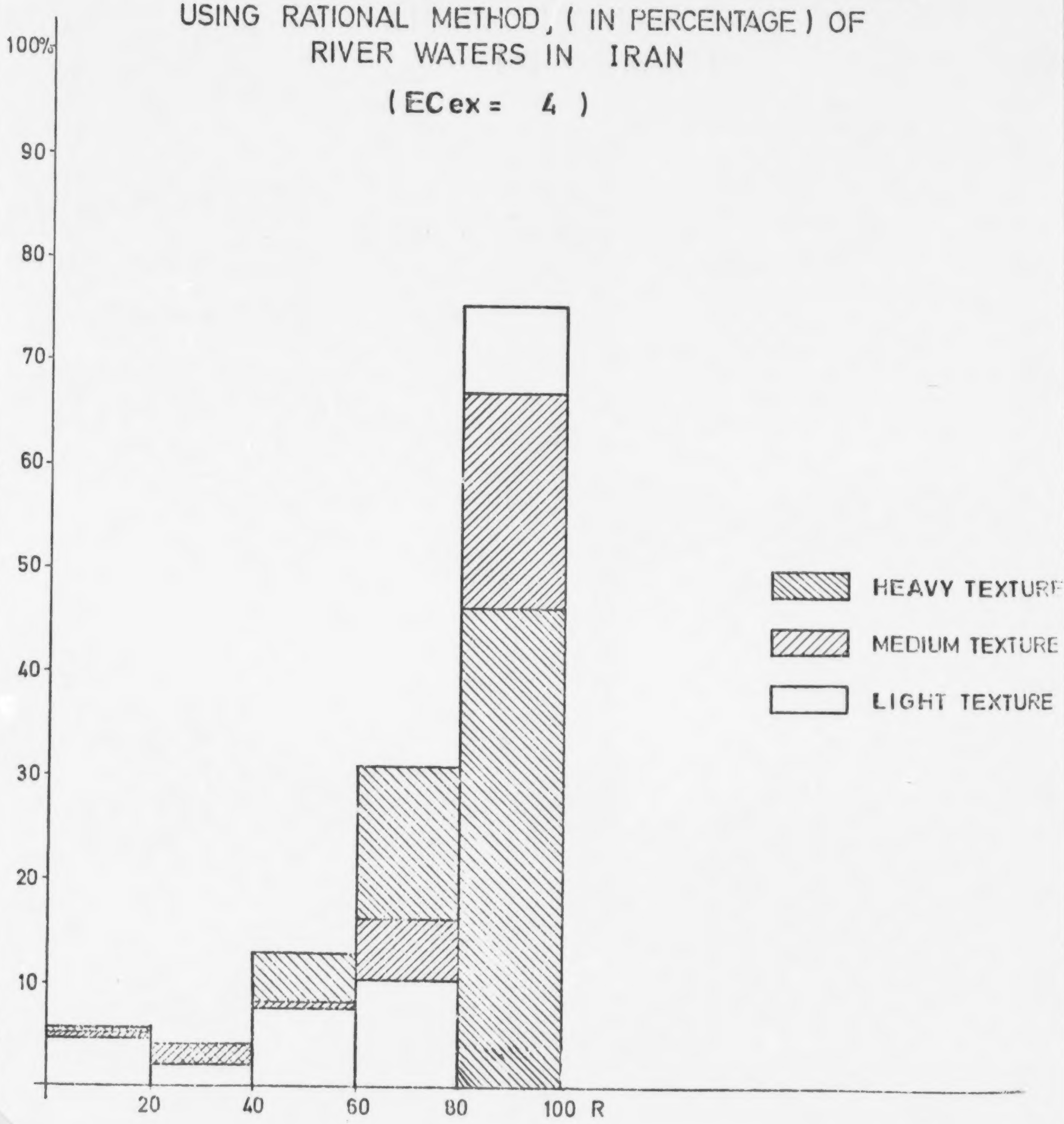

FIG 2 DISTRIBUTION OF SUITABILITY FOR IRRIGATION, USING RATIONAL METHOD, (IN PERCENTAGE) OF RIVER WATERS IN IRAN
(ECex = 12)

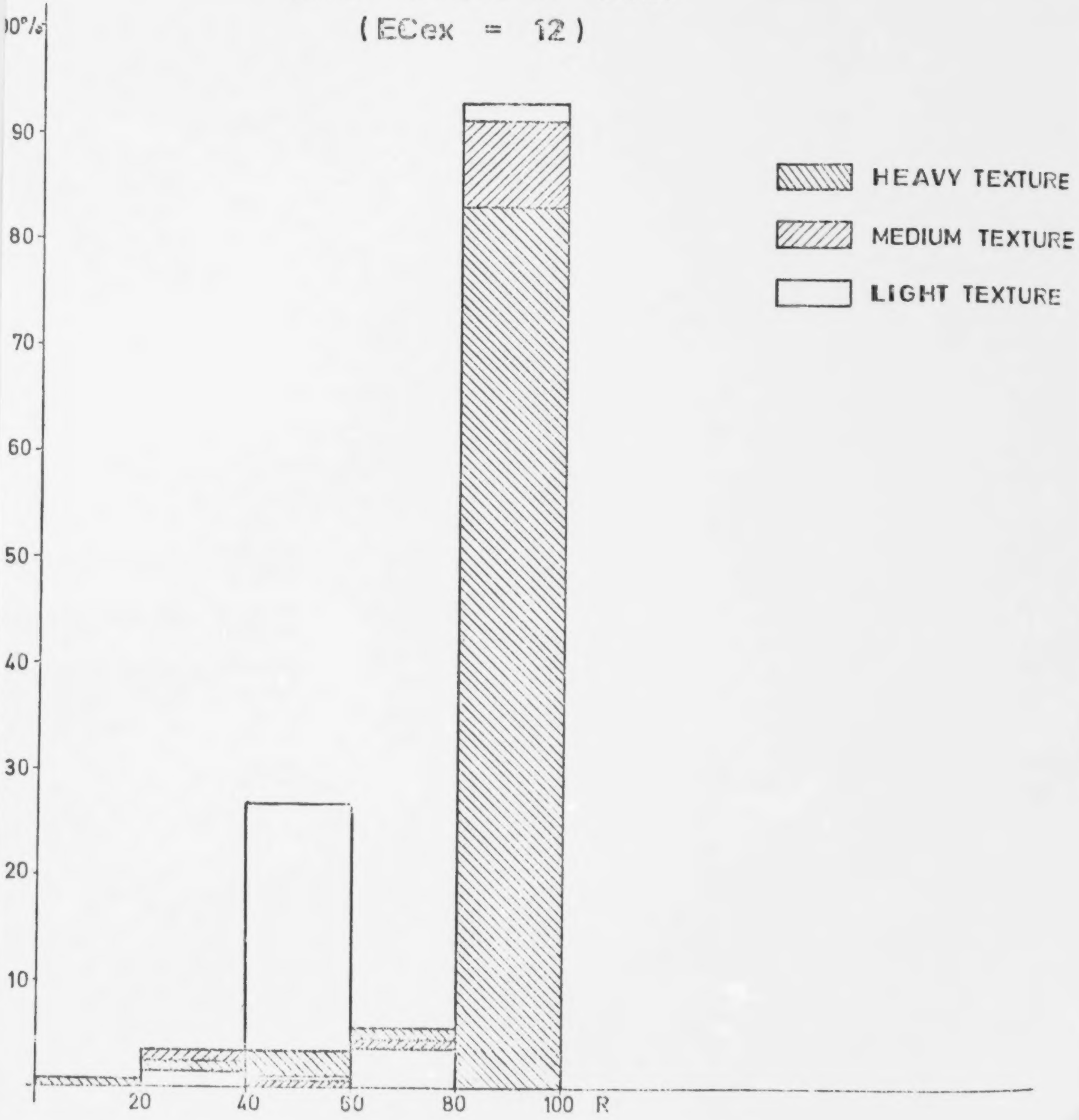

FIG 3 DISTRIBUTION OF SUITABILITY FOR IRRIGATION, USING RATIONAL METHOD, (IN PERCENTAGE) OF RIVER WATERS IN IRAN (ECex = 8)

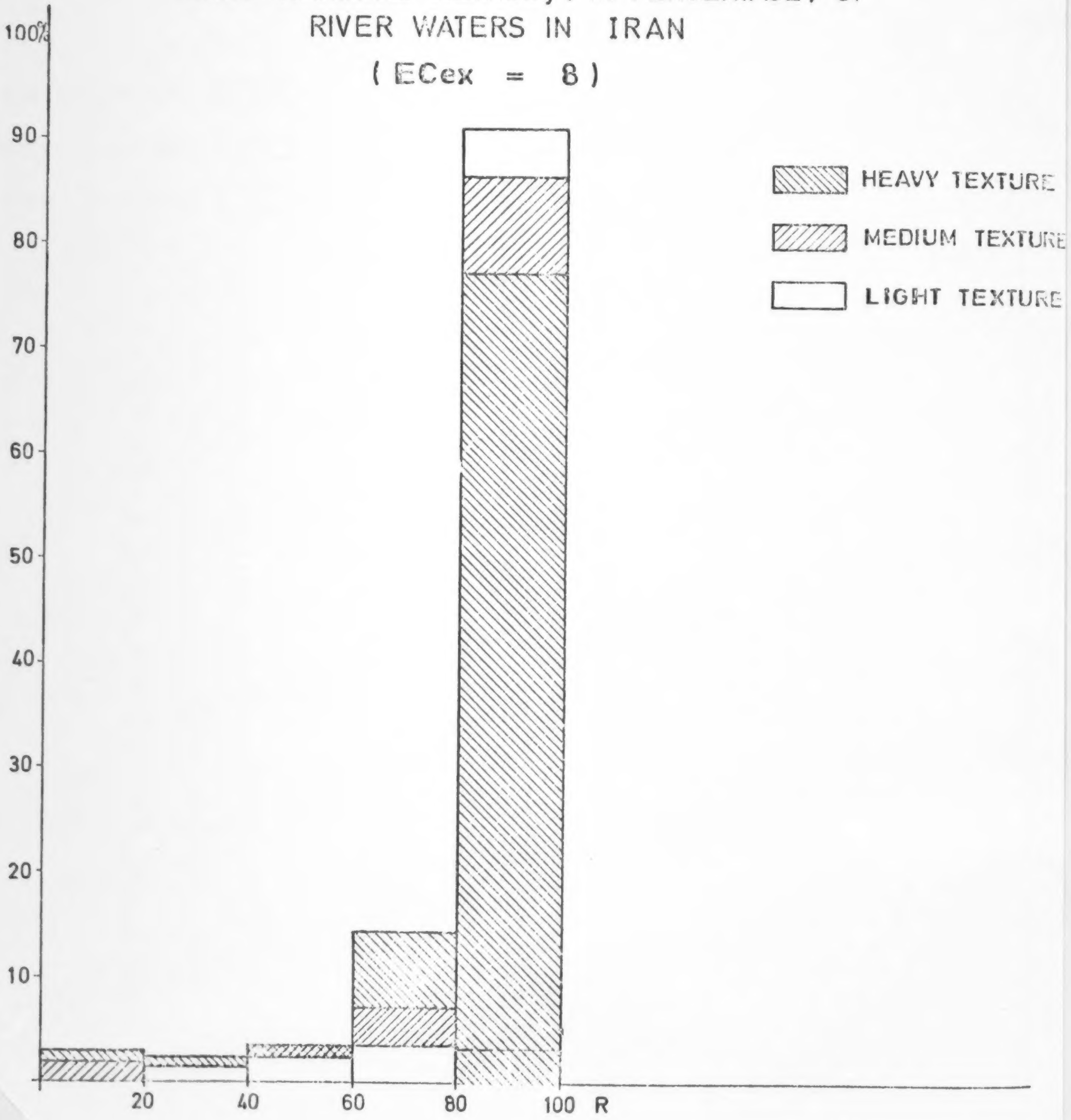

FIG 4 DISTRIBUTION OF SUITABILITY FOR IRRIGATION, USING RATIONAL METHOD, (IN PERCENTAGE) OF RIVER WATERS IN IRAN

(ECex = 16)

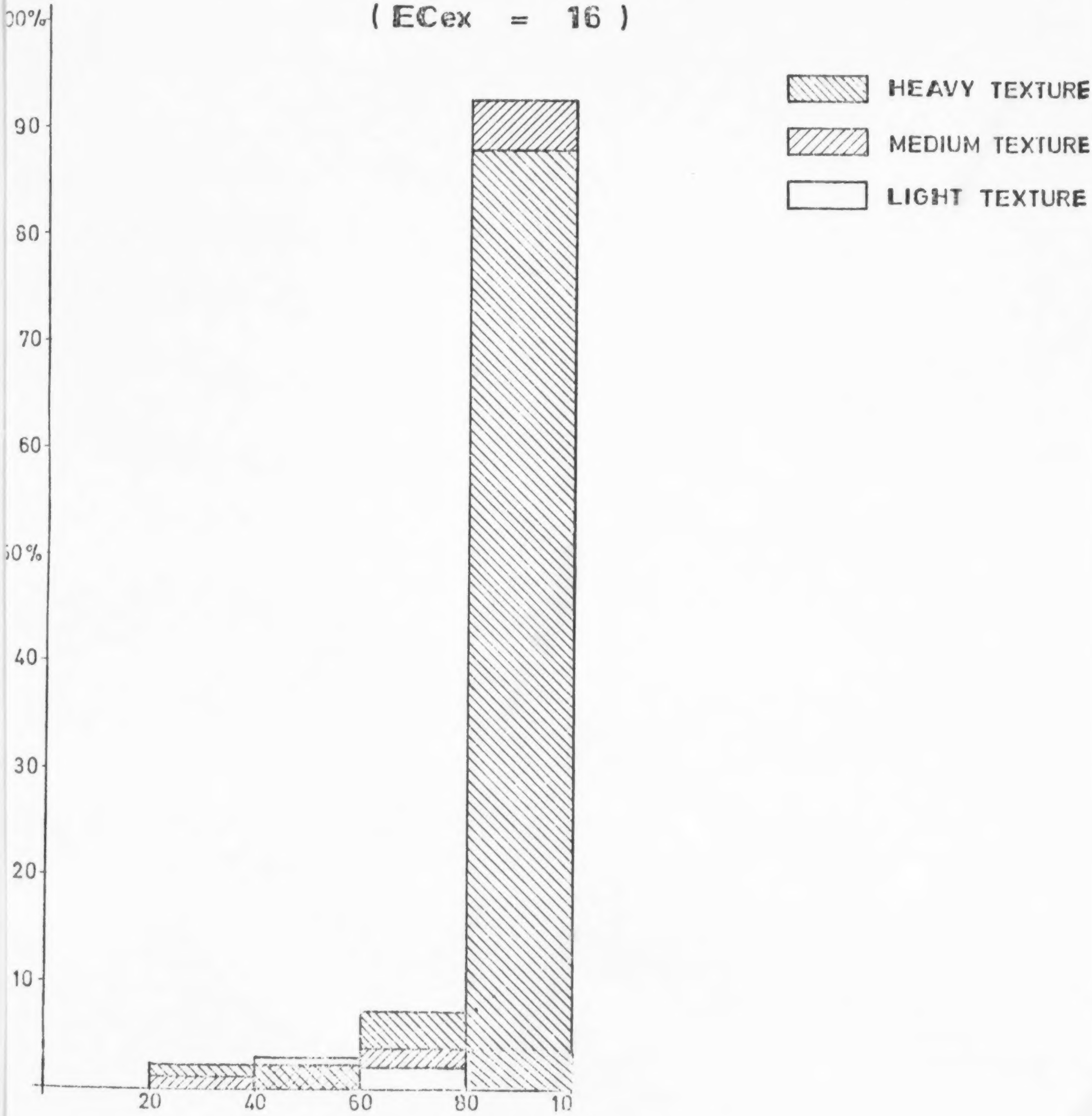

Table 2: Limit of EC of water with variation in plant, soil and irrigation efficiency.

ECex	R K	80	60	40	20	0
16	0.3	2.23	5.3	4.93	17.45	32
	0.5	3.56	8	13.7	21.3	32
	0.7	4.77	9.14	16.39	23.58	32
12	0.3	1.67	4	7.45	13.09	24
	0.5	2.67	6	10.28	16	24
	0.7	3.57	6.86	12.29	17.68	24
8	0.3	1.12	2.67	4.97	8.73	16
	0.5	1.78	4	6.85	10.57	16
	0.7	2.38	4.57	8.2	11.79	16
4	0.3	0.56	1.33	2.48	4.36	8
	0.5	0.89	2	3.42	5.33	8
	0.7	1.19	2.29	4.1	5.89	8

As can be seen from Table 2, the acceptable limit of EC for irrigation water can be as low as 0.56 mmho/cm if the crop to be grown is salt sensitive (ECex = 4), the soil is five textured (K = 0.3), and the irrigation efficiency is high (leaching fraction is 0.2; R = 80). If the crop is salt tolerant (ECex = 16), the soil is coarse textured (K = 0.7), and the leaching efficiency is near zero (leaching fraction near 1.0; R = 0), then an EC up to 32 is acceptable for the irrigation water. An EC above 32 is not considered acceptable under any combination of circumstances.

The EC of most rivers of Iran varies from 0.2 to 12.9 mmhos/cm, depending on geographical conditions. Therefore, their EC are below the critical limit as mentioned above.

Also from Table 2 we see that for the plant with a salt tolerance equal to 16 mmhos/cm, and 12 mmhos/cm none of the water is of good quality for irrigation, if the irrigation efficiency is 60% or less according to the U.S.S.L. method, for crops having a salt tolerance of 8 and 4 mmhos/cm, the waters with irrigation efficiency less than 40% and 20% respectively are out of the U.S.S.L. diagram.

As can be seen from Table 1, the percentage of class 1 waters according to the rational method is very high. This means a large percentage of the river waters of Iran is suitable for irrigation of all types of soils and plants. This is true even for heavy soils and for plants with a salt tolerance as low as 4 mmhos/cm. The percent of Iranian river waters falling into the various water quality classes, according to the Rational method and the U. S. Salinity Laboratory (USSL) method is shown in Table 3.

Table 3: Comparison between U.S.S.L. and Rational method for the distribution of suitability of river waters of Iran for irrigation

	EC, micromhos/cm				
U.S. Salinity Laboratory					
EC, mmhos/cm	250	250-750	750-2250	2250-5000	5000
Suitability class	I	II	III	IV	V
Percent of river waters in class	2.87	58.37	26.79	7.66	4.31
Rational					
Irrigation Efficiency	80	60	40	20	0
Suitability Classes	I	II	III	IV	V
Percent of river waters in class	82.21	9.56	4.25	2.15	1.83

We see clearly from Table 3 that according to the Rational method, 82.21% of these waters are in Class I whereas only 2.87% of the waters, according to U.S.S.L., are in Class I. The difference between the two classes is very high.

Considering that the irrigation efficiency in Iran, particularly by the traditional method is lower than 50%, we could say that the rational method for the evaluation of water quality for irrigation is more useful than the U.S.S.L. method.

SUMMARY

An irrigation water quality evaluation system (Rational system) devised for use in Iran has been presented. The system evaluates water quality with respect to salt tolerance of the crop to be grown, the permeability of the soil is inferred from soil texture, and irrigation efficiency. A total of 396 river waters in Iran have been classified according to the Rational system and that used by the U.S. Salinity Laboratory. Whereas only about 3 percent of the waters are in Class I in the latter system, 82 percent are in Class I in the Rational system.

REFERENCES

Massoumi, A. M. 1975. The rational method for evaluation of saline waters for irrigation. Journal of Environment, University of Tehran, No. 3. pp. 165-170.

Shalhevet, Y. 1973. Irrigation with saline water, in Arid Zone Irrigation, Chapman and Hall, London. pp. 263-266.

U. S. Salinity Laboratory Staff 1954. Diagnosis and improvement of saline and alkali soils. Handbook 60. pp. 79-81.

Van der Molen, W. H. 1967. Drainage for salinity control, sixth International Course on Land Drainage, Wageningen, The Netherlands. pp. 3-7.

CHEMICAL RECLAMATION OF SOLONETZ-SOLOCHAKS IN THE ARARAT PLAIN AND THE POSSIBILITY OF UTILIZING SALINE WATERS FOR LEACHING AND IRRIGATION

G. P. Petrosian 1/

INTRODUCTION

Due to the high level of saline groundwaters, reclamation of soda solonetz-solonchaks is very difficult. The nature of the soil salinization and the hydrogeological conditions add to the many problems of their reclamation.

The intense alkaline reaction due to the occurrence of sodium bicarbonate in the soil causes the swelling of colloids which brings about unfavorable physical properties in solonetz-solonchaks. The alkaline reaction of the soil medium inactivates the calcium and magnesium cations of the soil solution, thus reducing their effect in reclamation and resulting in toxic reactions in plants.

The nature of salinization of solonetz-solonchaks of the Ararat Plain in the Armenian SSR related closely to the chemistry of groundwaters which flow from the mountains and foothills.

The major part of the saline groundwaters (approximately 1/3 of the groundwater in the Republic) appear within the area of the Ararat Plain. The degree of salinity of the groundwaters increases considerably from the upper part of the watershed to the zone of discharge. The chemical composition of groundwaters varies greatly depending upon the geological structure and mineralogical makeup of the parent rock through which the waters percolate.

The role of water circulating through andesito-basalts containing sodium bicarbonate is especially important. Groundwaters enriched by carbonate salts are strongly alkaline. As the groundwaters rise to the surface by capillary movement, sodium bicarbonate is changed into sodium carbonate, giving rise to the formation of soda saline soils in areas with shallow carbonate groundwaters.

As sodium carbonate and bicarbonate accumulate along with sulfates and chlorides, the soil acquires the sodic type of salinization with a pH value of 9.0-11.0 (Fig. 1).

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RECLAMATION PROCEDURES

As a result of amelioration measures carried on in Armenia since 1963, application of waste sulfuric acid and by-products of the mining industry containing iron sulfate opened new prospects for reclaiming these soils.

By using effective drainage systems to bring the concentration of salts down to the threshold tolerable for plants, it was possible to desalinize the soils in a very short period of time.

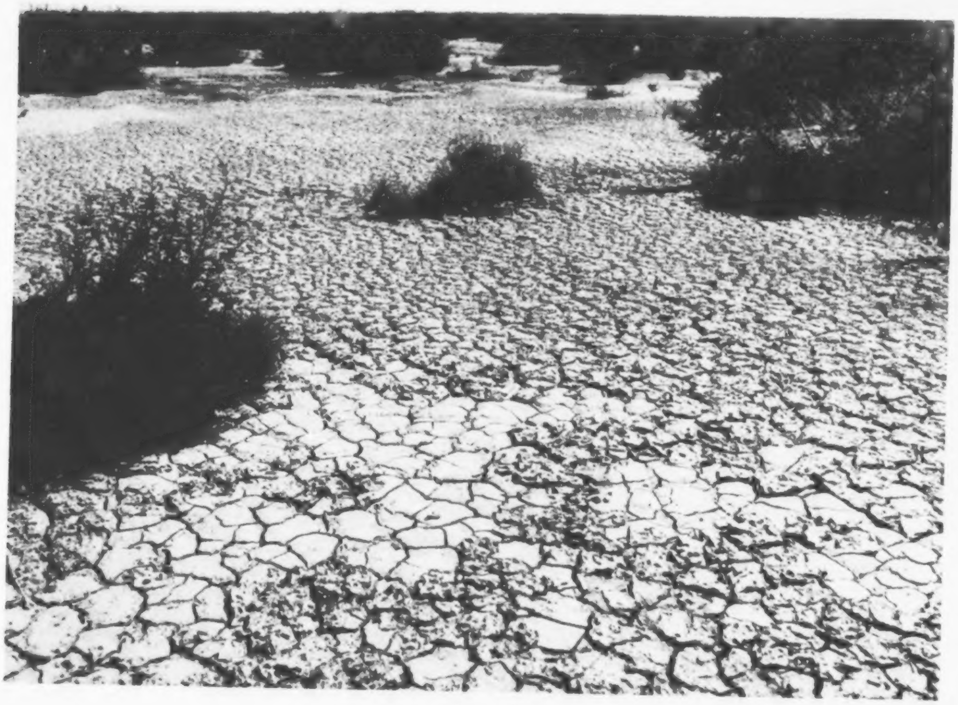

Figure 1. Solonetz-Solonchaks

Adding dilute sulfuric acid (0.8-1.0%) and iron sulfate to the soil brings about the neutralization of the alkaline reaction and replaces sodium by calcium in the exchange complex. In addition, the hydrophilic colloids are coagulated and dispersion of the soil is significantly reduced, which results in an increase in the soil permeability and desalinization during the leaching process.

During the neutralization of the alkaline reaction, the decomposition of magnesium and calcium carbonates with the formation of gypsum and sodium and magnesium sulfates also occurs. While leaching, the soluble salts and newly formed compounds of magnesium and sodium sulfate are carried out of the soil to the drainage outflow.

The newly formed gypsum differs considerably from the natural gypsum by its uniform distribution and high solubility. When the soil is leached, the gradually-dissolving newly-formed gypsum has a significant ameliorative influence on the soil by increasing the calcium ion composition of the soil solution and the base exchange complex.

During the decomposition of calcium and magnesium carbonates, CO_2 is discharged, a part of which is absorbed by the leached water, and the solubility of calcium and magnesium carbonates is increased. Further, the calcium and magnesium cations also participate in the reclamation process of the saline soils. (Fig. 2.)

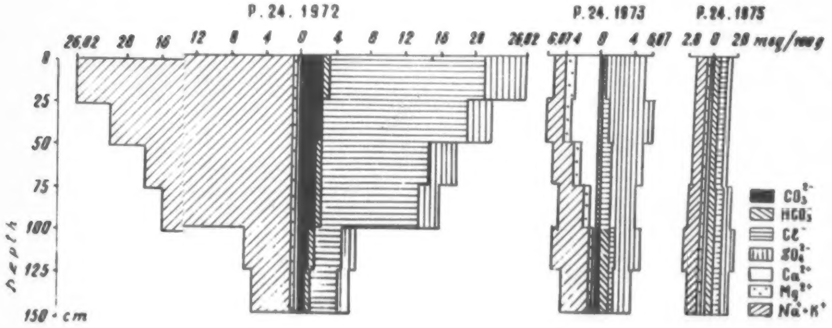

Figure 2: Salt profile of solonetz-solonchaks before and after chemical reclamation.

SOIL AGGREGATION

The ameliorative influence of iron sulfate is due not only to the formation of free sulfuric acid during the acid hydrolysis but also with the dehydration ability of the polyvalent Fe, which apparently increases the water permeability of soils.

Due to the radical improvement in the infiltration characteristics of the soil, it was possible to complete the leaching operations during a 3-5 months period.

Approximately 70-90% of the silt in solonetz-solonchaks is dispersed. After reclamation of the total, with iron sulfate, it has been observed that silt aggregation increases considerably. (Fig. 3.). Under the influence of active Fe, an irreversible aggregation of silt takes place.

Investigations carried out in the soil climatic conditions of the Ararat Plain showed that the aggregation of dispersed silt is accompanied by the absorption of soluble Fe from the soil solution.

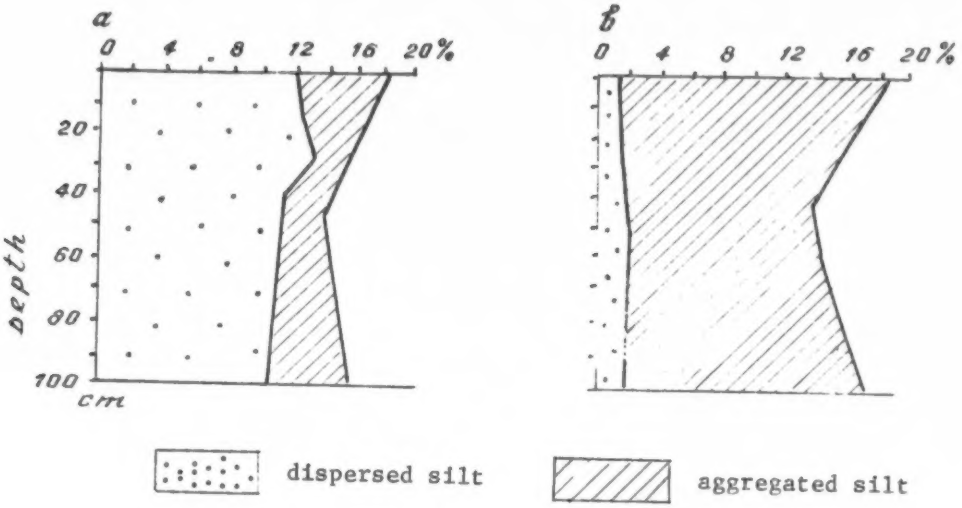

Figure 3: The content of dispersed and aggregated silt in the solonetz-solonchaks soil before (a) and after (b) chemical reclamation.

Silt aggregation and the decrease of the dispersion factor (DF) (Fig. 4) increase the infiltration rate. Solonetz-solonchaks have practically zero infiltration rate, but reach about 0.82 meters per day in the reclaimed soils (Fig. 5).

The machines used for the application of chemical amendments are specially designed and include automatic devices used for calculating the concentration of sulfuric acid introduced into the soil. Taking into consideration the salinity and texture of the soil, an estimation of the necessary amount of amendments and leaching water has been developed.

The amount of amendments and leaching water are as follows: sulfuric acid, 50 to 120 tons/ha; iron sulfate, 120 to 250 tons/ha; and leaching water, 20 to 50 thousand m^3/ha.

Reclamation was accomplished through the use of horizontal and/or vertical drainage. Based on the status of reclamation and the type irrigation, and in accordance with the growth requirements of crops, an application system for mineral fertilizers and a complex of agrotechnical measures was devised. Different varieties of annual and perennial crops were selected. The improved lands yielded 45-50 c/ha [2] of winter wheat, 90-100 c/ha of alfalfa and grapes, and 250-350 c/ha of different varieties of fruits, vegetables, melons, and geraniums (Figs. 6 & 7).

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[2] c/ha = centner/ha = 100 kg/ha.

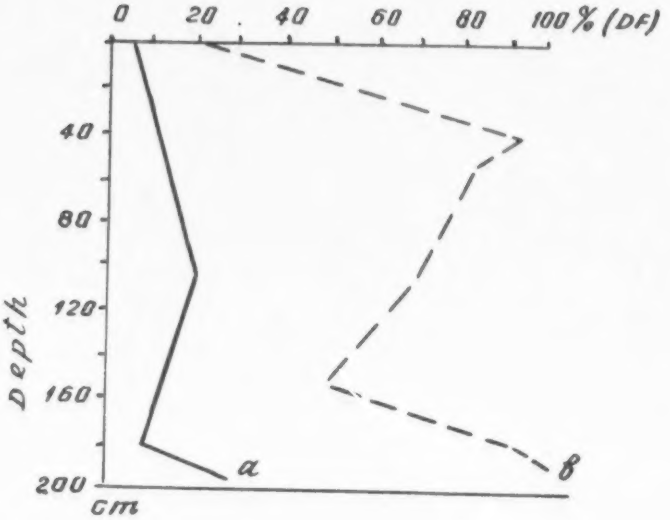

Figure 4: Dispersion Factor (DF) of Solonetz-Solonchaks before (a) and after (b) Chemical Reclamation.

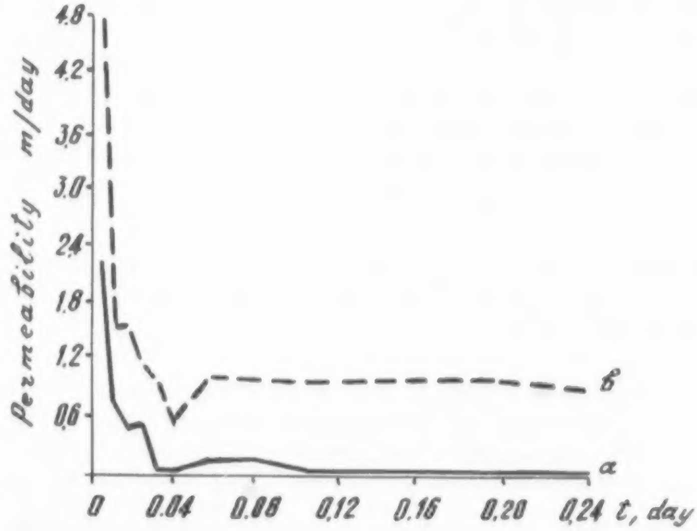

Figure 5: Water Permeability of Solonetz-Solonchaks before (a) and after (b) Chemical Reclamation.

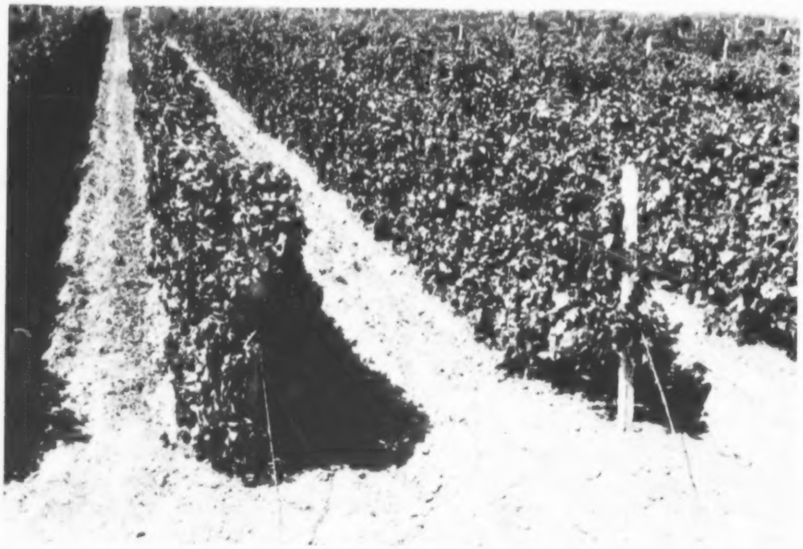

Figure 6. Vineyards on Reclaimed Soils.

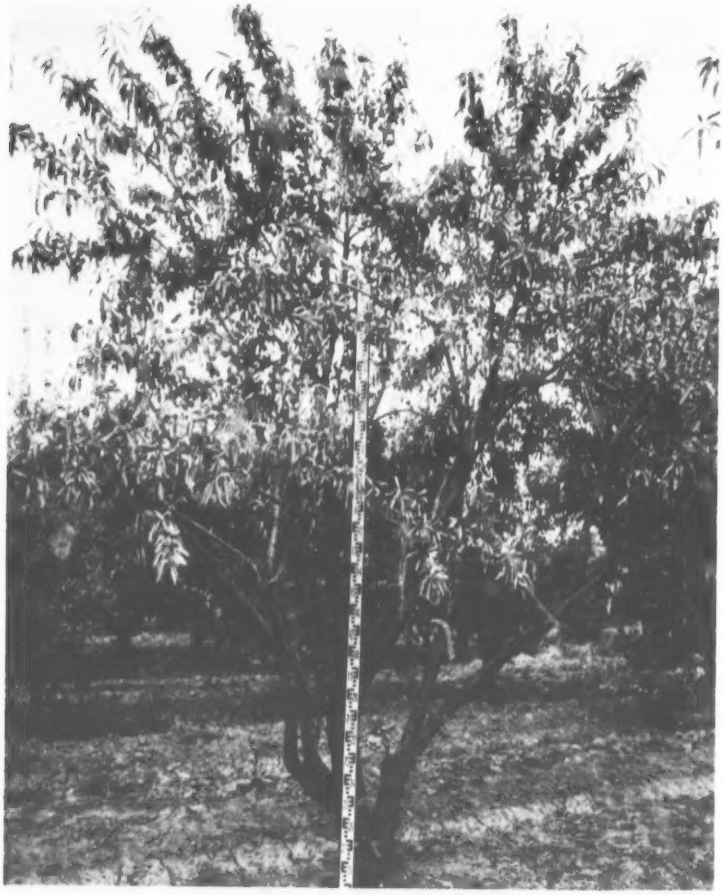

Figure 7. Orchards on Reclaimed Soils.

The cost of capital investments on the reclaimed plots will be paid off in 3-6 years. The rate of return depends upon the kind of crops being produced.

WATER QUALITY

Large-scale reclamation of salt affected soils brought new problems as the reclamation program expanded. There was a large increase in saline drainage water and a shortage of low-salt surface water for irrigation. For that reason, it was essential to develop measures for utilizing the outflow drainage waters for leaching and irrigation purposes. Conditions were complicated by the deterioration of the quality of the irrigation waters and salinization of the outflow drainage waters, whose salinity increased from 1.5-2.0 g/l to 8.0-10.0 g/l following intensive leachings. Considering, also, the fact that a significant part of the water sources for ameliorative purposes possess different degrees of salinity, a variable approach must be used for their application (Table 1).

Before the drainage waters are used for irrigation, their quality should be evaluated to check if they are suited for use. When evaluating irrigated waters according to Stabler, the Irrigation Coefficient ranges between 19-20. According to the Ion Exchange Coefficient (K), suggested by I. N. Antipov-Karataev and G. M. Kader, the investigated waters are also suitable for irrigation, as $K>1$.

The Ion Exchange Coefficient is calculated by the following formula:

$$K = \frac{rCa + rMg}{rNa + 0.23C}$$

where rCa, rMg and rNa are the contents of cations in water and C is the salinity of water, in g/l. K values are correlated reasonably well (negatively) with the Sodium Absorption Ratio (SAR) suggested by the U. S. Salinity Laboratory.

The chemical composition of artesian water is stable and very suitable for irrigation according to the criterion appraisals. The ground waters pumped from a depth of 40-50 m are also fit for irrigation, but they need a systematic control because their chemical composition is subject to definite seasonal changes. The utilization of these waters to irrigate the drained, reclaimed sites for a period of 13-15 years caused salinization of the soil columns at, and below, the level of groundwater table.

The groundwaters of virgin solonetz-solonchak soils containing up to 4.2-5.2 g/l soluble salts, with a strong sodium character ($Na/(Ca + Mg)>4$), an Irrigation Coefficient less than 2, and a SAR value of more than 20, are not recommended for irrigation. They may be used only for leaching when introducing chemical amendments into the soil.

Table 1: Chemical Characteristics of Water Sources of the Reclamation Station

Time of Sampling	Depth of ground-water table (m)	pH	Total Soluble Salts g/l	Meq/l							Irrigation Co-efficient (Stabler)	Ion Ex-change Co-efficient (Antipov-Karataev)	SAR+
				CO_3	Total CO + HCO_3	Cl	SO_4	Ca	Mg	Na+K*			
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Irrigation Water													
1970		8.73	0.657	1.60	3.40	2.59	2.50	2.10	2.88	3.51	20.8	1.36	2.2
1976		8.40	0.726	1.12	4.46	2.70	2.34	2.35	4.84	2.31	21.3	2.90	1.2
Artesian Water													
1970	130.0	8.85	0.341	0.80	2.40	1.21	0.60	1.30	1.15	1.76	43.6	1.33	1.2
1976		7.80	0.360	0.14	2.12	0.96	0.79	1.30	0.96	1.61	52.8	1.33	1.1
Pumped Water													
1970	50.0	8.50	0.680	1.60	2.80	3.81	3.27	2.29	3.53	4.06	14.9	1.38	2.4
1976		7.70	0.918	0.74	5.44	5.98	2.74	2.60	7.20	4.36	9.6	2.14	2.0
1970		8.70	0.986	2.00	3.20	6.80	3.20	2.60	2.96	7.64	8.3	0.71	4.6
1976		7.80	0.886	0.66	4.06	7.38	2.83	4.10	7.20	2.97	7.8	3.56	1.2
Horizontal Drainage No. 2, Chemical Reclamation Accomplished in 1972-1974													
1975- Sept.	3.0	7.55	5.792	1.84	15.28	32.24	19.61	2.80	28.00	36.33	1.7	0.82	9.3
1975- Dec.		8.50	5.060	3.86	13.34	20.70	24.70	1.60	15.36	41.78	2.3	0.39	14.3
1976- March		8.15	5.550	2.40	15.28	33.92	34.98	3.30	24.52	56.36	1.5	0.48	15.1
1976- June		8.00	6.292	0.73	14.40	32.56	23.69	8.00	25.28	37.37	1.7	0.85	9.2
Vertical Drainage No. 9, Chemical Reclamation Accomplished in 1960-1962													
1975- Sept.	3.0	7.90	1.792	1.60	10.96	5.08	10.27	1.50	5.76	19.05	4.0	0.37	10.0
1975- Dec.		8.05	1.104	1.43	11.62	5.70	9.90	2.35	6.08	18.79	4.1	0.44	9.1
1976- March		7.96	1.908	2.40	12.34	7.22	11.60	1.44	8.20	21.52	3.9	0.44	9.8
1976- June		8.02	1.708	1.60	12.04	5.53	9.61	1.35	7.20	18.63	4.0	0.45	9.0

* Calculated as difference between total anions and Ca + Mg.
+ Sodium Absorption Ratio.

Table 1 Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Collector Receiver of Drainage Water													
1975-Sept.	4.0	8.82	1.756	2.86	8.06	6.66	8.28	1.00	5.12	16.88	4.7	0.35	9.7
1975-Dec.		8.45	1.720	1.43	8.02	5.65	9.42	2.70	4.72	15.67	6.6	0.46	8.1
1976-March		8.50	1.180	1.60	6.89	4.48	5.26	1.55	3.60	17.38	6.4	0.29	7.1
1976-June		8.10	1.392	0.46	8.80	6.72	4.68	1.20	6.72	12.18	6.1	0.71	6.2
Groundwaters of Solonetz-Solonchak (Virgin Soil)													
1960	1.5	9.40	4.202	2.47	11.34	38.73	15.24	3.12	6.15	56.04	1.2	0.16	26.0
1976	2.8	7.82	5.523	0.46	5.84	60.88	7.44	3.30	12.48	58.38	0.9	0.26	20.8
Groundwaters of Orchard and Vineyard Undrained Site													
P-2.1-IY	2.8	8.60	2.552	1.32	17.78	18.59	9.15	2.60	18.86	24.06	2.9	0.87	7.3
P-2.1Y-X	1.4	9.22	4.420	1.60	20.73	30.43	20.32	2.81	14.38	54.29	1.4	0.31	18.5
P-9.1-IY	2.85	8.47	2.772	0.32	17.59	10.91	4.04	1.60	11.34	19.60	2.7	0.64	7.7
P-9.1Y-X	1.50	9.90	3.873	3.17	18.81	18.46	9.22	1.80	16.79	27.90	2.8	0.64	9.1

SECONDARY SALINIZATION

Secondary salinization of soils has also been observed after chemical reclamation in areas where the drainage water was ponded in a collector network and the groundwater level raised to a depth of 1.2-1.5 m from the soil surface. Upward movement of groundwater led to secondary salinization. The hazard of secondary salinization may be prevented by irrigating on the same schedule as non-saline soils.

From 1953 until 1974 investigations were carried out to study the effect of slightly saline groundwaters on reclaimed soil, plant growth, and development and production of fruit crops and grapevines.

During the period of May-October, the investigated areas of undrained sites revealed that the groundwater level rose sharply to a depth of 1.2-1.5 m from the surface. The lowering of the groundwater table was observed only at the end of autumn, after terminating the irrigations. During the growth season when intensive water consumption took place, the root systems of the plants were under the influence of groundwaters. In some periods of the season the salinity of the water increased up to 4.420 g/l, the carbonates to 1.32-3.17 and the bicarbonates to 17.59-20.73 meq/l (Table 1).

In spite of unfavorable conditions during the period, secondary salinization process has not been observed. A frequent and heavy system of irrigation provided leaching, which prevented capillary accumulation of salts from groundwaters in the zone of plant roots.

These experiments have been conducted on undrained small plots of approximately 10 hectares, hence, the results may not be valid for larger areas. Soil reclamation has been measured by the improvement in the condition of the reclaimed soil rather than by the effect on crop yield.

The study of soil-hydrogeological conditions of the Ararat Plain shows that there is a necessity for lowering the groundwater table on reclaimed areas to a depth of three meters to prevent capillary accumulation of soluble salts and secondary salinization of soils, as well as to speeding up leaching processes during chemical reclamation.

The groundwater salinization is independent of the reclaimability of the soil. During the process of land reclamation due to the influence of tillage methods, irrigation regime, and the biological peculiarities of cultivated crops, further desalinization of soils occurs which is expressed in reduced amounts of salts and the degree of salinization of groundwaters. While the soil desalinization process during the chemical reclamation takes a short time, the desalinization of groundwaters requires quite a long time.

Salinization of drainage outflow waters from the areas which were reclaimed in 1972-1974 is very high and approximately similar to that of groundwaters from virgin solonetz-solonchak. However, drainage waters from the areas improved in 1960-1962 are markedly desalted. The drop in salinity occurred mostly on account of the decrease in the amount of chlorides, sulfates and magnesium.

Drainage waters from the reclaimed areas were low in salts and had, to some degree, an increased Irrigation Coefficient. Nevertheless, high concentrations of carbonates and bicarbonates were registered, and these waters may be used only for leaching purposes under favorable drainage conditions. When utilizing them for irrigation purposes, the sodium hazard must be considered. The degree of salinity in collector waters is relatively low due to the mixing of more saline waters flowing from recently reclaimed areas with less saline waters transported from already improved lands. The salinity of drainage water in collectors, according to long term results, does not exceed 1.35 to 1.75 g/l, while the concentration of bicarbonates is within limits of 7.48-9.20 meq/l.

Reducing the salinity of drainage water before using it for reclamation is not necessary when the water has the above mentioned chemical composition. A problem arises, however, when the water is to be used for irrigation purposes. Gypsum treatment of water is not profitable because of its low solubility and high labor,machinery, and transportation costs for mixing the gypsum, cleaning the equipment, and disposing of residues in the dispensers. It is not likely that investigators' recommendations to treat the soil with gypsum every 2 to 3 years to neutralize the carbonates and bicarbonates formed when utilizing alkaline groundwaters will be acceptable. The most economical, advantageous, and efficient method is the application of concentrated waste sulfuric acid supplied into the drainage water by means of an automatic dispenser.

IRRIGATION WATER TREATMENT

In order to neutralize the alkaline reaction, the calculated leaching requirement of sulfuric acid is obtained from the concentration of bicarbonates. Thus, the calculated norm of sulfuric acid is equivalent to the content of HCO_3. To neutralize 1,000m^3 of drainage water, with 16.24 meq/l HCO_3 concentration, 795 Kg of waste sulfuric acid (calculated at 100% pure sulfuric acid) is required, and for 8.16 meq/l concentration, 400 Kg, respectively (Table 2).

In irrigation, artesian, and pumped waters of the Ararat Plain, the content of bicarbonates is within the limits of 3.40-4.96 meq/l and, on undrained sites, does not give rise to exchangeable sodium accumulation. Accordingly, the calculated norms for sulfuric acid addition may be reduced by 20-30% when the concentration of bicarbonates in water is more than 10 meq/l. And if the concentration is less than 10 meq/l, the calculated norm may be reduced by 50%. Introduction of sulfuric acid is carried out in one stage.

Table 2: Some characteristics of drainage water before and after applying concentrated (96%) sulfuric acid and fresh irrigation water.

Added H_2SO_4					Meq/1									
Kg/ 1000 m^3 water	% of calculated norm	Ratio of treated and untreated water	pH	Total soluble salts g/1	CO_3	Total CO_3 + HCO_3	Cl	SO_4	Ca	Mg	Na+K*	Irrigation Coefficient (Stabler)	Ion Exchange Coefficient (Antipov-Karataev)	SAR+
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Drainage Water before Applying H_2SO_4														
			8.20	5.312	1.58	16.24	26.96	28.50	7.80	23.04	40.86	1.9	0.7	10.4
After Applying H_2SO_4														
795	100		5.90	6.056	-	-	26.28	31.02	7.30	23.52	26.48	2.2	1.1	6.7
597	75		6.45	5.824	-	4.66	26.40	32.28	8.00	22.56	32.78	2.1	0.9	8.4
398	50		6.70	5.808	-	8.06	26.38	30.08	7.50	23.32	33.50	2.1	0.9	8.5
Water of Collector before Applying H_2SO_4														
			8.65	1.616	1.52	8.16	7.00	11.18	2.60	4.96	18.78	5.5	0.4	9.7
After Applying H_2SO_4														
400	100		6.20	1.726	-	-	6.82	15.92	3.10	4.68	14.96	6.8	0.5	7.6
300	75		6.75	1.608	-	2.32	6.74	15.34	3.10	4.64	16.66	6.6	0.4	8.5
200	50		7.15	1.656	-	4.56	6.82	11.00	3.10	4.64	14.58	6.9	0.5	7.4
Irrigation Water														
			8.50	0.726	1.12	4.96	2.42	2.24	2.40	5.12	2.10	23.8	3.3	1.1
Water of Collector Mixed with Irrigation Water 1:1														
			8.52	0.932	1.24	6.34	4.56	4.70	2.70	4.16	8.74	10.7	0.8	4.7

*Calculated as difference between total anions and Ca + Mg.
+Sodium Absorption Ratio.

Table 2 Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Water of Collector after Reclaiming with Mixed Irrigation Water														
400	100	1:1	7.30	1.576	-	2.88	4.52	8.56	3.20	4.00	8.76	10.7	0.8	4.6
400	100	1:0.75	7.10	1.086	-	2.56	4.96	9.32	2.90	4.00	9.94	9.7	0.7	5.3
400	100	1:0.50	7.00	1.020	-	2.32	5.30	10.56	3.10	4.16	10.92	9.0	0.6	5.7
400	100	1:0.25	6.85	1.304	-	1.60	5.76	12.10	2.80	4.32	12.34	8.1	0.6	6.5
300	75	1:1	7.34	0.992	-	3.68	4.40	7.66	3.00	4.00	8.74	10.9	0.8	4.7
300	75	1:0.75	7.35	1.152	-	3.64	4.74	8.70	2.80	4.16	10.12	9.9	0.7	5.4
300	75	1:0.50	7.32	1.400	-	3.12	5.48	9.60	3.00	4.32	10.88	8.8	0.6	5.7
300	75	1:0.25	7.30	1.108	-	2.88	5.98	9.20	3.00	4.48	10.58	8.3	0.7	5.5
200	50	1:1	7.75	0.902	-	4.46	4.52	6.70	2.80	4.16	10.92	9.9	0.6	5.8
200	50	1:0.75	7.80	0.948	-	4.66	4.80	7.48	2.60	4.64	9.70	10.0	0.7	5.1
200	50	1:0.50	7.82	0.796	-	4.54	5.36	8.64	3.20	3.28	12.06	8.6	0.5	6.7
200	50	1:0.25	7.75	0.836	-	4.40	5.70	9.48	2.70	4.80	12.08	8.2	0.6	6.2

In the presence of sufficient amounts of irrigation water it is possible to considerably reduce the salinity and bicarbonate content of drainage water by mixing it with fresh waters without applying chemical amendments.

IRRIGATION METHODS

Irrigation methods are important for determining the possibility of utilizing slightly saline waters for irrigation. Heavy rates of irrigation by sprinkling and flooding cause leaching of salts from the soil. With furrow irrigation, the salt is diffused causing its redistribution and accumulation between the furrows. Furrow irrigation, therefore, is not recommended until the soils are completely desalinized.

SUMMARY

Waste sulfuric acid and iron sulfate are the most efficient amendments for improving soda saline soils. Their ameliorative influence can be observed in a very short time. Applying sulfuric acid and iron sulfate causes neutralization of the alkaline reaction and desalinization of the soil, sharply increasing infiltration rate and permeability.

On reclaimed soils high-yielding annual and perennial crops are cultivated, securing very quick returns on capital investments.

Saline waters with an alkaline nature and salt concentration of no more than 2.0-2.5 g/l may be used for leaching provided the groundwater table is lowered to a depth of 3.0 m. When using them for irrigation, the alkaline reaction should be previously neutralized.

Concentrated waste sulfuric acid is the most efficient and profitable amendment for neutralizing the carbonate and bicarbonates. When the concentration of bicarbonates in water is over 10.0 meq/l the equivalent norm of sulfuric acid may be reduced by 25%, and if the concentration of bicarbonates is lower, the reduction may equal 50%. Desalinization of saline waters may also be accomplished by mixing them with irrigation water.

YIELDS AND ACREAGE AS VARIABLES IN PLANNING THE USE OF SALINE IRRIGATION WATER: A CASE STUDY FROM IRAN

H. Diestel 1/ and W. Treitz 2/

INTRODUCTION

The problem of matching the irrigation water quantities available to the quantities demanded is only one aspect of planning and managing irrigation. The salinity of irrigation water, which may vary with the source and with time, has economic consequences which also must be taken into consideration.

It is remarkable how frequently the aspect of the quality of the various waters supplied is not dealt with when the use of various water sources is integrated. A simple example will show the importance of this aspect. Assume that 18% permanent leaching is used with irrigation water of 300 ppm. In the long run, there are practically no salinity limitations to growing most vegetables. A 900 ppm water source is now developed, and this water is mixed 50/50 with the 300 ppm water. The permanent leaching requirement becomes 33% or, if it is desired to maintain it at 18%, it becomes uneconomical to grow most vegetables. In many areas of the world, e.g., in India (Bains, 1969) or in Venezuela (Pla, 1975), the possibility of leaching, which might be one of the reasons for the "water quantity thinking", is very limited or even non-existent, and the salinity of the irrigation water becomes a dominating factor. Moore (1972) has focussed attention on the economic importance of irrigation water quality. Moore et al. (1974) have attempted to obtain figures in dollars and cents for the values per unit of irrigation water quantity and irrigation water salinity considering a long period of time and a whole project area.

There is also an economic value to the time during which irrigation water has a given quality. Cavazza (1969) describes conditions (supplemental irrigation from wells in a coastal area with winter rainfalls) under which agriculture can be carried out with irrigation waters which reach high salinities for certain periods of time. Zur and Bresler (1973) came to the conclusion that under short irrigation intervals, the osmotic component of the soil water potential is of dominating importance, and that this component is dominated by the pre-irrigation salt content of the soil. The tolerance of plants to salinity can change during the growing season. Considerable work has been done since 1967 on the problem of finding the optimal combination of water quantity and water salinity for specific cases

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within one growing season (Bresler, 1967; Yaron and Bresler, 1970; Bresler and Yaron, 1972; Yaron et al., 1972; Zur and Bresler, 1973). The implications of this work for time periods of several years and for larger project areas are obvious (Yaron et al., 1974). In this study, as will be seen, only long term considerations with average yearly figures were adequate.

The decision to implement a project should always be based on economic criteria. All data available on the engineering, hydrological, plant physiological and pedological aspects should be channelled so as to supply, within a time fixed by the planning schedule, information with which these economic criteria can be calculated. The purpose of this paper is to demonstrate and to expose to discussion how a problem of economical plannning with irrigation water quality, as it posed itself in a preliminary planning study, has been solved.

To avoid constant repetition, reference will not always be made to the reports from which the information is drawn. Details on the possibilities and consequences of reducing the salinity of the Hableh Rud River are given in Diestel (1969) and Treitz and Diestel (1969). Information on all aspects of the planned development of the Garmser Plain, as well as a listing of relevant reports, is given in Roberts (1970).

PROJECT ALTERNATIVES

Conditions

About 120 km south-east of Tehran, an alluvial fan of about 50,000 ha (hectares) created by the Hableh Rud River extends from the foot of the Alburz mountains into the Great Salt Desert of central Iran. As the water supply is inadequate , the cultivated areas tend to be separate from each other, each one surrounding a village. 13,500 ha are cultivated in a normal (not dry, not wet) year by 3,410 full-time farmers; 21,550 ha of land are at the disposal of these farmers. At the apex of the fan, most of the river flow is diverted into approximately 70 small unlined irrigation canals. The whole area is referred to as the Garmsar Plain. The average yearly precipitation, a quantity which is neglected in the following, is approximately 100 mm. The soils (see also Dewan and Famouri, 1964) are light to medium textured in the upper and central parts of the plain, and medium to heavy textured in the central and lower parts of the plain. 23,450 ha of soil are irrigable. In about 19,000 ha of these, the salt content is 0.15-0.35% (electrical conductivity of the saturation extract 4-8 millimhos/cm). The soils have, in general, good natural drainage.

When floods in the river arrive at the diversion system at the apex of the fan, the upper reaches of the ditches are filled up with sediment or destroyed relatively quickly, with the result that most of the flood waters flow through the old river gullies. The 21-year average discharge of the

Hableh Rud in flood free months is 6.20 m^3/sec or 195.53 MCM (million cubic meters) per year.

The average electrical conductivity of the river water (ECiw) during normal ("flood free") flow is 1.678 mmhos/cm (3 decimals used for arithmetic reasons). The SAR of the river water at the head of the alluvial fan is around 6. Thus, the water is of high salinity and low sodium hazard. A small proportion of the total irrigation water used is taken from a number of deep wells, hand dug shallow wells, and ghanats. The quality of the groundwater is poor. The use of this water is disregarded in this paper.

Table 1. Soil and water salinities with the project alternatives

Item	Project Alternatives				
	No change, normal year	Increased yields		Increased cropping area	
		Constant flow diversion scheme	Retention basins scheme	Constant flow diversion scheme	Retention basins scheme
Viw, MCM	135.53	131.84	126.04	131.84	126.04
Vcw, MCM	99.31	99.31	99.31	108.56	103.78
Vuw+dw for k≈0.4, MCM	36.22	32.53	26.73	23.28	22.26
(Vuw+dw/Viw)100	26.72	24.67	21.21	17.66	17.61
Vuw+dw ratio	1.0	0.898	0.738	0.643	0.615
LP for k=1	13.53	12.15	9.99	8.70	8.32
ECiw, millimhos/cm	1.678	1.109	1.109	1.109	1.109
ECdw, millimhos/cm (est.)	12.400	9.128	11.101	12.400	12.400
ECe, millimhos/cm	6.200	4.564	5.551	6.200	6.200
Cropping area, ha	13,550	13,550	13,550	14,812	14,160
Increase in cropping area, ha		0	0	1,262	610
Mean depth of water applied m^3/ha/year	10,002	9,730	9,302	8,901	8,901

Viw = Volume of irrigation water; MCM = Million cubic meters; Vcw = Volume of water used consumptively; Vuw = Volume of water unaccounted for; Vdw = Volume of drainage water; k = Leaching coefficient; Vuw+dw ratio = ratio of projected Vuw+dw to original Vuw+dw; LP = Leaching percentage; ECiw = Electrical conductivity of irrigation water; ECdw = Electrical conductivity of drainage water (estimated); ECe = Electrical conductivity of saturation extract.

In the lower part of the Hableh Rud watershed, the main river itself and several of its tributaries cut through formations which are rich in salt. These tributaries contribute about 4% to the flood free water discharge, but about 50% to the salt discharge. Plans to reduce the harmful effect of these tributaries were put forward. Despite the salinity of the water, agricultural operations have been carried out for hundreds of years.

From surveys of the area and experiments, a weighted average of 7,329 m^3/ha was obtained as preliminary consumptive use figure for the area. This figure is weighted for crops and for crop areas. Thus, the total annual amount of consumptive water on 13,550 ha is estimated as 99.31 MCM, termed Vcw in the following. Water balance studies and seepage measurements in the ditches showed that about 60 MCM of water are lost yearly through ditch seepage and other losses. Thus, 135.53 MCM are applied on the average each year as irrigation water (Viw).

The weighted average of the electrical conductivity of the saturation extract of the soils in the plain is 6.2 mmhos/cm (ECe) . Following a common approximation (Richards, 1954; Arar, 1971; van Hoorn, 1971), the electrical conductivity of the soil solution at field capacity, i.e., the conductivity of the drainage water (ECdw) can be taken as 2 x ECe, which is 12.4 mmhos/cm. The theoretical permanent leaching percentage (LP) for average conditions in the plain would be 13.5, based on 100% efficiency. However, 36.22 MCM are applied in excess of the Dcw every year. If the water balance given for the plain would be perfect, and if the whole 36.22 MCM are leaching water, this would correspond to a LP of 26.7, and a leaching coefficient, k, of 0.5, which seems a low value. The leaching coefficient is the ratio of the ECdw calculated from LP to the actual ECdw. In view of the uncertainties involved in assigning values to the terms of the water balance (see Table 1, column 1) it was not attempted to separate leaching water and water which is not accounted for (Vuw). Both quantities together shall be termed Vuw + dw here. It was not attempted to estimate a k-value for the plain. In all cases, the quantities given under Vuw + dw will allow for expected k-values and thus for achievement of the given ECdw-values.

Constant Flow Diversion Scheme

Technical Description and Costs of the Scheme

Based on investigations in the watershed and on studies of the engineering feasibility of diversion works, seven tributaries, the flow of which could be diverted, were singled out. The constant flow salt evacuation project provides for structures which guide the flood free surface flow and most of the subflow of the tributaries into a pipeline along the Hableh Rud, which, in turn, delivers the waste flow to an evacuation channel in the Garmsar Plain.

The estimated total diverted surface and subsurface flow of the seven tributaries is 0.117 m^3/sec. This water will have an estimated concentration of 20 kg/m^3. The theoretical average flood free discharge of the Hableh Rud can thus be estimated as 6.083 m^3/sec with a concentration of 0.710 kg/m^3 (1.109 mmhos/cm). The diversion of 3.69 MCM of water leaves a flood free yearly volume of 191.84 at the diversion point, which, reduced by the losses of 60 MCM, amounts to 131.84 MCM for irrigation. The improvement in quality from about 1,000 to 700 ppm is very nearly the inverse of the deterioration of the Colorado River at Imperial Dam from 700 ppm in 1944 to the anticipated 1,000 ppm in 1980 (Moore et al., 1974).

The construction costs for this scheme have been estimated as 67,173,500 Iranian rials, the yearly operation and maintenance costs as 1,026,250 rials. During the time the studies were made, 1 US $ was equivalent to about 75 Iranian rials.

Increases in Yields Resulting from the Scheme

The quantity of water supplied will be reduced by 3%. However, in the long run, the change in water quality will effect a reduction in soil salinity if the area irrigated without project implementation, is irrigated with the water supplied with project implementation. In a normal year, the Vuw + dw will be 32.53 MCM (Table 1). It is now assumed that the reduction in the quantity of leaching water applied will be as great as the reduction in Vuw + dw. Thus, if the fraction which effected leaching was 13.53% so far with k=1, a leaching fraction of (32.53/36.22) x 13.53 = 12.15 will now effect leaching, which means practically no change in leaching applications with the water now having an EC of 1.109. The ECdw and ECe which will result in the long run are estimated as 9.128 and 4.564 mmhos/cm (this corresponds to assuming that the water balance given is perfect: Vuw + dw = Vdw, k = 0.5). No data were available on the change in yield between ECe of 6.2 and 4.6 for the crops grown in Garmsar. Data of Bernstein (1964, 1965) were used realizing limitations in their application for these conditions. Bernstein's data were plotted, and the yield changes obtained by interpolation. That this is unsatisfactory - but unavoidable because of lack of the appropriate data - does not need to be stressed. For melons, no changes in yield were assumed because of the rather special cultivation practices used with the persian melon (kharbozeh) which involve heavy pre-irrigation, and because of strong doubts on the applicability of Bernstein's data for this crop. The yield increases used are listed in Table 2. Most of the values are so low that their physical reality may be doubted. But for economic evaluation, they must be accepted as indicating order of magnitude.

Increases in Irrigated Area Resulting from the Scheme

The LP with k = 1, which is 13.53 without project implementation, would be 8.94 with implementation. Thus, less total irrigation water could be applied without a loss in productivity, and the water no longer needed for leaching used to irrigate additional land. It is assumed that it will be

Table 2

DATA FOR THE ECONOMIC AND FINANCIAL ANALYSIS (in Million rials per year where applicable)

			Wheat Grain/Straw	Barley Grain/Straw	Fodder Barley	Melon	Cotton	Figs + Pomegranates	Alfalfa	Total	Row
		Normal year cropping area (ha)(948 ha fallow)	6640	678	948	2033	1355	678	270	13550	1
Constant Flow Diversion Scheme	Increased yields	% yield increase	3.5	1.0	2.5	0	0.5	10.5	15		2
		Total value of added output	3.000/0.350	0.060/0.010	0.235	0	0.075	1.000	0.609	5.340	3
		Total value of added input from outside	0.146	0.004	0	0	0	0	0	0.150	4
		Total annual expenditures with project implemtation	47.436	4.382	4.476	9.514	11.957	6.237	2.174	86.176	5
		Total annual value of farm output	98.999	6.953	9.715	15.857	16.335	10.492	4.659	163.010	6
	Increased area	Increase in cropping area (ha) (88 ha fallow)	617	63	88	189	126	63	25	1262	7
		Additional value added due to area increase	7.361	0.506	0.678	1.361	1.341	0.813	0.355	12.415	8
Retention Basins Scheme	Increased yields	% yield increase	2.0	0.5	1.5	0	0.5	4.5	6.0		9
		Total value of added output	1.716/0.200	0.028/0.005	0.140	0	0.075	0.430	0.243	2.837	10
		Total value of added input from outside	0.086	0.003	0	0	0	0	0	0.089	11
		Total annual expenditures with project implemtation	47.257	4.374	4.476	9.514	11.957	6.195	2.714	85.947	12
		Total annual value of farm output	97.565	6.916	9.620	15.857	16.335	9.919	4.293	160.505	13
	Increased area	Increase in cropping area (ha) (43 ha fallow)	298	31	42	91	61	30	12	610	14
		Additional value added due to area increase	3.555	0.249	0.323	0.655	0.649	0.387	0.170	5.988	15

possible, by information from farmers and by a change in water supply, to reduce the Vuw + dw by the same proportion as the required leaching is reduced, i.e. by 8.70/13.53 = 0.643 or 2/3. Thus, only 17.66% of the Diw will be "unaccounted for" and used for leaching, leaving 108.56 MCM for consumptive use in a normal year, allowing irrigation of 14,812 ha, 1,262 ha more than without project implementation. As, other factors remaining unchanged, no stimulus would exist to substantially change the working habits of the farmers, the assumption was made that the areas cultivated with the various crops would increase in proportion to the total increase in irrigated area. The average cropping areas listed in Table 2 would result (88 ha fallow not listed).

Retention Basins Scheme

Technical Description and Costs of the Scheme

Another project provided for collecting basins for the water of the same saline tributaries emptied at controlled intervals into the main river. Emptying the salt water basins could be timed in such a way that the salty water would reach the apex of the alluvial fan at night at a given time. The intakes of the irrigation ditches would be closed and irrigation interrupted during that night. The salty water would pass in a few hours through the most suitable river gully into the desert. Compared to the constant flow diversion scheme, this one would necessitate additional water losses, namely the river water flowing during the evacuation time, estimated as 5 hours per week. The Viw available would be only 126.04 MCM in an average year. The construction costs of this scheme were estimated as 45,250,000 rials, the yearly operation and maintenance costs as 876,250 rials.

Increases in Yields Resulting from the Scheme

By reasoning analogous to the Constant Flow Diversion Scheme (see Table 1) it can be estimated that, if the Viw is used on the acreage cultivated without project implementation, in the long run an ECe of 5.55 mmhos/cm would result (see Table 1). With the mentioned data of Bernstein, the percentage in yield increases shown in Table 2 were estimated.

Increases in Irrigated Area Resulting from the Scheme

Following the reasoning of Constant Flow Diversion Scheme, a Vcw of 103.78 MCM can be estimated for a normal year (Table 1) which makes irrigation of 14,160 ha possible, 610 ha more than without project implementation. The cropping areas listed in Table 2 would result.

EVALUATION OF THE PROJECT ALTERNATIVES

General Remarks

Once it has been shown that it can be expected that the proposed project alternatives will be technically feasible, they must be evaluated from the economic (or social or national) and from the financial (or private) points of view. The economic analysis will show whether there is a benefit to the whole society from the resources committed to the project alternatives. As indicators of economic worthiness, the value-added, the benefit-cost ratio, the internal rate of return, and the capital/net benefit ratio were used. The financial analysis will identify a possible financial profitability of the schemes to the individual participants in the project alternatives - in this case the farmers of the Garmsar area.

It is important to note that, in this paper, only national and private benefits from crop production are considered. Livestock production (mainly sheep and goats, most of them spending the summer months in the mountains) was not included in this discussion.

Value-Added

Materials and services are purchased by the participants of a project from participants in the national economy who are not participants in the project. Through the use of its own internal resources, a project is able to produce values from these external inputs and to sell them to members of the national economy outside the project. The difference between the value of the project output and the value of the external inputs into the project is termed the "value added" by the project. It is the economic contribution of the scheme to the national economy.

For the whole Garmsar area, the total value of sales and home consumption was estimated. From this, the total value of fertilizers, chemicals, and machinery was subtracted. This figure, 133.4 Million rials, represents the value added without implementation of salinity reduction. In estimating the value added for the four alternatives, an important difference exists depending on the use of the improved water. If it is used to increase the yields on the area irrigated without project implementation, only the costs for "imported" machinery for harvesting the higher yields have to be subtracted from the value of output and home consumption (rows 4 and 11, Table 2). The additional total value-added figures per average year thus obtained are given in Table 3.

The Benefit-Cost Ratio

The benefit-cost ratio is obtained by dividing the present worth of the expected stream of benefits, in this case the yearly value added, by the present worth of the expected stream of costs, in this case the cost of capital investment and operation and maintenance per year. If this ratio is larger than one, the scheme is considered economically justified. In this study, secondary benefits were not considered, only tangible, primary, direct benefits which can be assigned a monetary value. In calculating the present worth, a discounting rate of 15% was used in order to obtain conservative, i.e. low, benefit-cost ratios. A discounting period of 50 years was taken. (For an explanation of the calculation of the benefit-cost ratio, see Gittinger 1972). Investment costs were assumed to accrue to 1/2 in each of the two construction years. It can be seen (Table 3) that, at this high interest rate, only one alternative is just about justifiable by the standard of this ratio. There are, however, limitations to the applicability of this economic indicator (Bergmann 1973).

Table 3. Economic indicators, in million rials, unless not applicable or otherwise indicated.

	Constant Flow Diversion Scheme		Retention Basins Scheme	
Investment Costs	67.2		45.2	
Yearly Operation and Maintenance Costs	1.0		0.8	
	Incr. Yields	Incr. Area	Incr. Yields	Incr. Area
Economic Analysis				
Additional total value added per year	5.19	12.42	2.75	5.99
Internal rate of return, %	6	14	4	9
Benefit-cost ratio	0.42	0.90	0.33	0.64
Capital-net benefit ratio	12.9	5.4	16.4	7.5
Financial Analysis				
Additional total farm income per year				
a) Without water charges				
1) total	4.80	6.71	2.52	3.24
2) per average farm, rials	1,408	1,967	739	950
b) With water charges				
1) total	1.18	3.09	-0.04	0.68
2) per average farm, rials	346	906	-12	199

The Internal Rate of Return

The internal rate of return is the discounting rate at which the benefit-cost ratio is equal to one. It is thus a measure of the earning which is obtained from the investment into a project. Internal rates of return equal to or larger than about 15% are considered satisfactory. The values for this indicator are given in Table 3. Again, only one scheme is acceptable by this standard.

The Capital - Net Benefit Ratio

This ratio, obtained from the division of the investment sum by the yearly value added, is, with certain qualifications, a measure of the time in years in which a project will pay back. As values smaller than 4.5 are considered satisfactory for this ratio, again only one scheme is acceptable (Table 3).

Financial Analysis

Without project implementation, the estimated total annual farm income from crop production in the Garmsar Plain is 72.035 million rials. There are 3,410 farms, therefore an average figure, which has a mainly arithmetical meaning but gives an idea of orders of magnitude, is 21,125 rials per year and farm. To obtain the farm income, the value of output was determined. From this figure, the expenditures for the following items were deducted: seed, fertilizer, chemicals, tractor service for land preparation and harvest, hired labor, land, water, and interest. For the increase in yield alternatives, the value of output is increased by the percentages in rows 2 and 9 of Table 2, to obtain the values in rows 6 and 13 of this table; to obtain the farm expenditures with implementation, the expenditures for machinery and hired labor for harvest were increased by the percentages by which the yields are expected to increase, and interest (4%) on the additional expenditures was added to the expenses without implementation. Under the local conditions, these additional expenses will only accrue for wheat, barley, cotton, and figs/pomegranates (rows 5 and 12, Table 2). For the increased area alternatives, the total increase in farm income for the area is calculated by multiplying the per ha farm income without project implementation (5,316 rls) by the increases in cropping area (Table 1, 2). No cost item for purchasing and preparing new land, which might be expected, is taken into account, as there are about 8,000 ha farm land which are not cultivated in a normal year.

For the economic and financial analysis, it was assumed that the existing information system, through which the water allocation is channelled, can be used at no additional costs to inform the farmers about the consequences of implemented schemes. Much can be achieved by controlled water supply, for which costs are being incurred also without project implementation. Total and per farm figures for the increases in farm income from crop production are given under the heading "a" in Table 3. However, it might be argued that the farms should carry some or all of the costs of the projects.

Based on 50 years and 3% for the fixed investments, the yearly costs for the schemes including operation and maintenance are 3.62 million rials for the constant flow diversion scheme, and 2.56 million rials for the retention basins scheme. Under the heading "b" in Table 3, additional farm incomes are given for the case that the farmers carry the full costs of the scheme. In one case, there would be even a reduction in income.

CONCLUSIONS

The yearly value added per m^3 of normal flow unimproved river water is 133.4 million rials/195.53 MCM = 0.68 rials. One can estimate, based on the constant flow diversion scheme with a reasoning as shown above, that, if the water would be improved to 0.1 mmhos/cm, 17,700 ha could be irrigated in a normal year, an increase by 4,150 ha. The value added from each ha of land is 9,845 rls. With "perfect" water, the yearly value added from the plain would be 133.4 + 40.86 = 174.26 million rials. Each micromho/cm of normal flow Hableh Rud water brings a damage of 40.86 million rials/(1678-100) micromhos/cm = 25,894 rials to the national economy. An improvement by 569 micromhos/cm by the constant flow diversion scheme results in 1,262 new irrigable hectares, which means that an improvement by 0.45 micromhos/cm is as valuable as providing for 10,002 m^3 of additional irrigation water of the present quality: both measures make irrigation of one additional hectares physically possible, and for both measures the national economy could pay up to 9,845 rls/year. The farmers of the Garmsar Plain could pay up to 5,316 rls for each ha gained, i.e. for each 0.45 micromhos/cm improvement or 10,002 m^3 additional unchanged quality water. The actual cost of 0.45 micromhos/cm improvement are 3.62 million rls/569 micromhos/cm x 0.45 = 2,836 rls/year. Hekket (1964, 1968) has estimated that a canal system replacing the traditional distribution system, costing 160 million rials, would save about 40 MCM per year conveyance losses. The yearly cost for such a scheme would be 9.12 million rials (Treitz and Samadani, 1969), or 2,280 rials per 10,002 m^3. Thus in this specific case, it is only about 25% more expensive to gain 1 ha of land by salinity reduction than by providing additional water, based on a comparison with a quantity gain through an improved system.

Not only is it a repetition to state that there are many problems attached to the estimation of river discharge (in this case decisive for the value of Viw) and of consumptive use figures (Vcw), it is also repetitious to say that more information on yield-salinity interrelations is needed. Nevertheless, the plea shall be made here again to recognize the importance of obtaining and publishing more such data. Economic planning with water quality must rely completely on data which give, for the area in question, the increase in income from additional sales made possible by reduction of soil salinity. Information is badly needed on whether and/or how data such as those of Bernstein (1964, 1965) are applicable to other conditions, and on yield depression below ECe values of 8 mmhos for salt tolerant crops. The latter information is important for economic planning with water quality in low income areas where most of the income stems from salt tolerant crops.

Based on the data shown, the conclusion can be drawn that, for both diversion schemes, the alternative to increase the irrigated area is more profitable than to increase the yields, both from the national and private points of view (Table 3). The relevant economic indicators are marginal, but they would justify the recommendation to plan in detail the reduction of the salinity of the Hableh Rud water with the constant flow diversion scheme as an individual project, using the improved water to increase the irrigated area. However, for the purpose of this paper, only the two schemes were considered which are exclusively planned to effect a change in river water quality. Further development possibilities exist. Of special interest for the Garmsar Plain is the implementation of a canal system. This system can be combined with a salt diversion scheme. Very costly items would become common items for both schemes. The reduction in investment costs resulting from such a combination would be considerably higher for the retention basins scheme than for the constant flow diversion scheme. A re-estimate of the salt diversion schemes additional to a canal system for the Garmsar Plain, including modifications of the salt diversion schemes, was made by Hekket (1973). Likewise not considered here are the possibilities to drill wells and/or to regulate the river which are both measures that also have water quantity and water quality implications, and the possibility to cope with salinity by changing the cropping pattern and/or cultural practices, or by land reclamation.

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BIBLIOGRAPHY

Arar, A. 1971. Irrigation and drainage in relation to salinity and water-logging. In: Irrigation and Drainage Paper No. 7, FAO, Rome: 86 - 111.

Bains, S.S. 1969. Tolerance of certain crops to salinity and high sub-soil saline water conditions. In: Value to Agriculture of High Quality Water from Nuclear Desalination, I.A.E.A., Vienna: 197 - 205.

Bergmann, H. 1973. Guide to the Economic Evaluation of Irrigation Projects. OEDC, Paris.

Bernstein, L. 1964. Salt tolerance of plants. Agric. Inf. Bull. No. 283, U.S.D.A.

Bernstein, L. 1965. Salt tolerance of fruit crops. Agric. Inf. Bull. No. 292, Agric. Res. Service, U.S.D.A.

Bresler, E. 1967. A model for tracing salt distribution in the soil profile and estimating the efficient combination of water quality and quantity under varying field conditions. Soil Sci.: 104: 227-233.

Bresler, E. and D. Yaron. 1972. Soil water regime in economic evaluation of salinity in irrigation. Water Resources Res. 8: 791 - 800.

Cavazza, L. 1969. Agronomic aspects of irrigation with brackish water in Southern Italy. In: Value to Agriculture of High-Quality Water from Nuclear Desalination. I.A.E.A., Vienna: 219 - 224.

Dewan, M.L. and J. Famouri. 1964. The Soils of Iran. FAO, Rome.

Diestel, H. 1969. Possibilities of Improving the Quality of the Water of the Hablehrud (Garmsar). FAO - UNDP Varamin Project, Tehran.

Hekket, H. 1964. Garmsar Irrigation Project. Independ. Irrig. Dept. of the Ministry of Water and Power, Tehran.

Hekket, H. 1968. Additional note to the Review of the Garmsar Irrig. Project, Tehran (as cited by Treitz and Samadani, 1969).

Hekket, H. 1973. Garmsar Irrigation Project. Study of Salt Reduction Works. Tehran Water Board, Tehran.

Moore, C.V. 1972. On the necessary and sufficient conditions for a long-term irrigated agriculture. Water Resources Bull. 8: 802 - 812.

Moore, C.V., J.H. Snyder, and P. Sun. 1974. Effects of Colorado River quality and supply on irrigated agriculture. Water Resources Res. 10: 137 - 144.

Pla, I. 1975. Salt and water balances in irrigated soils under tropical conditions. Proc. Intern. Symp. New Development in the Field of Salt Affected Soils, 1972. Ministry of Agriculture, Cairo.

Gittinger, J. Price. 1972. Economic Analysis of Agricultural Projects. Johns Hopkins Univ. Press., Baltimore - London.

Richards, L.A. Editor, 1954. Diagnosis and Improvement of Saline and Alkali Soils. Agric. Handbook No. 60, U.S.D.A.

Roberts, H. 1970. Integrated Planning of Irrigated Agriculture in the Varamin and Garmsar Plains, Iran. The Development Plan. UNDP/FAO, Rome.

Treitz, W. and H. Diestel. 1969. Economic Evaluation of Schemes to Reduce the Salinity of the Hableh Rud River (Garmsar). Varamin-Garmsar FAO - Special Fund Project in Cooperation with the Ministry of Agriculture Tehran.

Treitz, W. and F. Samadani. 1969. Appraisal Report of a Combined Canal System - Deep Wells Scheme for the Garmsar Plain. FAO-UNDP Varamin-Garmsar Project, Tehran.

Hoorn, J.W. van 1971. Quality of irrigation water, limits of use and prediction of long term effects. In: Irrigation and Drainage Paper No. 7, FAO, Rome: 117 - 135.

Yaron, D. and E. Bresler. 1970. A model for the economic evaluation of water quality in irrigation. Austral. J. Agric. Econ. 14: 53 - 62.

Yaron, D ., H. Bielorai, J. Shalhevet, and Y. Gavish. 1972. Estimation procedures for response functions of crops to soil water content and salinity. Water Resources Res. 8: 291 - 300.

Yaron, D., J. Shalhevet, and E. Bresler. 1974. Economic evaluation of water salinity in irrigation. The Hebrew University, Faculty of Agriculture, Jerusalem/Rehovot.

Zur, B. and E. Bresler. 1973. A model for the water and salt economy in irrigated agriculture. In: Physical Aspects of Soil Water and Salts in Ecosystems. Springer Verlag, Berlin-New York: 395 - 407.

MINIMIZING THE SALT BURDEN OF PECOS RIVER IRRIGATION DRAINAGE WATER

G.A. O'Connor and Chris Cull [1]

INTRODUCTION

The success of irrigated agriculture is dependent upon the control of soil salinity. To prevent the harmful accumulation of salts in soils, an additional quantity of water, over and above that required to meet evapotranspirational needs of a crop, must be passed through the root zone. This additional increment of water is known as the leaching requirement (USSL, 1954).

An estimate of the leaching requirement (LR) may be obtained from the salt balance concept and is given by the well known equation

$$LR = EC_{iw}/EC_{dw} \qquad (1)$$

where EC_{iw} and EC_{dw} refer to the electrical conductivities of the irrigation and drainage waters, respectively. The equation has been widely used and is generally regarded as resulting in conservative estimates of LR. One condition in which the equation may greatly overestimate the leaching requirement is when soil precipitation of salts added in the irrigation water is significant. Salt precipitation may be encouraged by careful irrigation water management; that is, applying as little leaching water as possible without allowing salts to accumulate in the soil to levels detrimental to the crop. This management technique is referred to as the minimum leaching concept.

Rhoades and co-workers (1973) evaluated the effect of minimized leaching on the composition of waters draining from large lysimeters filled with California soil and irrigated with eight important river waters of the Western United States. The salt burden of drainage waters was shown to depend on the water composition and on the leaching fraction (LF) used. Results with synthesized water similar to the Pecos River of New Mexico were especially dramatic, resulting in a reduction of drainage salt burden of almost 5 tons per acre (11 t/ha) per year when the LF was reduced from 0.3 to to 0.1. Minimized leaching also resulted in significant savings of applied irrigation water. Decreasing the amount of extra water used for leaching resulted in a savings of water diverted for irrigation of about 1 acre-foot per acre (9,000m^3/ha) per year. Thus, the Salinity Lab's data suggest a tremendous potential for the minimized leaching concept, and are especially encouraging for the Pecos River. The objective of our study was to evaluate this potential using Pecos River water applied to an agricultural soil common to the Pecos Valley. The overall verification of the minimized leaching concept under New Mexico conditions will consist of a laboratory study, a greenhouse study, and a field plot experiment to be conducted in the Pecos River Valley. The data reported here are for the laboratory study.

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EXPERIMENTAL PROCEDURES

The soil selected for study was the calcareous Reagan silt loam, a Typic Calciorthid. The Reagan soil comprises about 40 percent of the cultivated land in the Roswell-Artesia Basin of the Pecos River Valley and is well suited to irrigation. Bulk samples of the soil were collected, air dried, and ground to pass a 2mm sieve. The soil was then carefully packed into 9 (three per treatment) small plexiglass lysimeters 7.0 cm ID by 25.0 cm long. Soil depth was 20 cm and all columns were packed to a bulk density of 1.3 gr/cm^3 which approximates actual field conditions. Each lysimeter was equipped with a porous ceramic plate in the bottom of the column through which drainage water was collected under a suction of 22 cm Hg. Salinity sensors were positioned about 5.0 cm from the bottom of each column to monitor soil solution salinity.

Changes in the soil solution composition that result from irrigation management techniques are normally very slow to occur. Thus, multiple irrigations were necessary in our study to observe the effects of leaching treatment in as short a time span as possible. To aid in the evaporation of water from the soil surfaces (and hence maximize irrigation frequency), the lysimeters were placed in an evaporation chamber especially designed for the study (Fig. 1). Details of the chamber construction and performance have been reported previously (O'Connor and Cull, 1976). The chamber enclosed a slowly rotating dual turntable which supported the columns. Radiant heat for evaporation was supplied by tungsten heat lamps positioned 60 cm above the soil surface. The lamps supplied about 2×10^4 luxes of light intensity at the soil surface, and heated the air temperature within the chamber to about 50°C.

Drainage water was collected for analysis in receiver flasks positioned below the columns. Suction was supplied to each lysimeter via a vacuum line which entered the rear of the unit and connected to a small plexiglass vacuum chamber positioned in the center of the turntable. A tenth plexiglass column was also positioned on the turntable to measure free-water evaporation.

The leaching treatments consisted of irrigations with a synthesized Pecos River water with the following composition, all in meq/l: 17Ca, 9Mg, 11.5 Na, $3HCO_3$, $22.5SO_4$, and 12Cl. Irrigation water was applied for calculated leaching rates (LR) of 0.1, 0.2, and 0.4. The 40 percent leaching treatment was considered representative of the irrigation management currently used along the Pecos River. The 10 percent and 20 percent treatments were chosen to represent reduced (minimized) leaching treatments. The composition of the synthesized Pecos water used to irrigate the lysimeters was characteristic of the Pecos River at a point south of Artesia, New Mexico. A water with similar chemical properties was shown by Rhoades et al. (1974) to maximize the effects of reduced leaching.

Following irrigation at the prescribed leaching fractions, the columns were covered, weighed, and allowed to stand (without suction) for 48 hours. The covered columns were then subjected to a constant suction (22 cm Hg) for

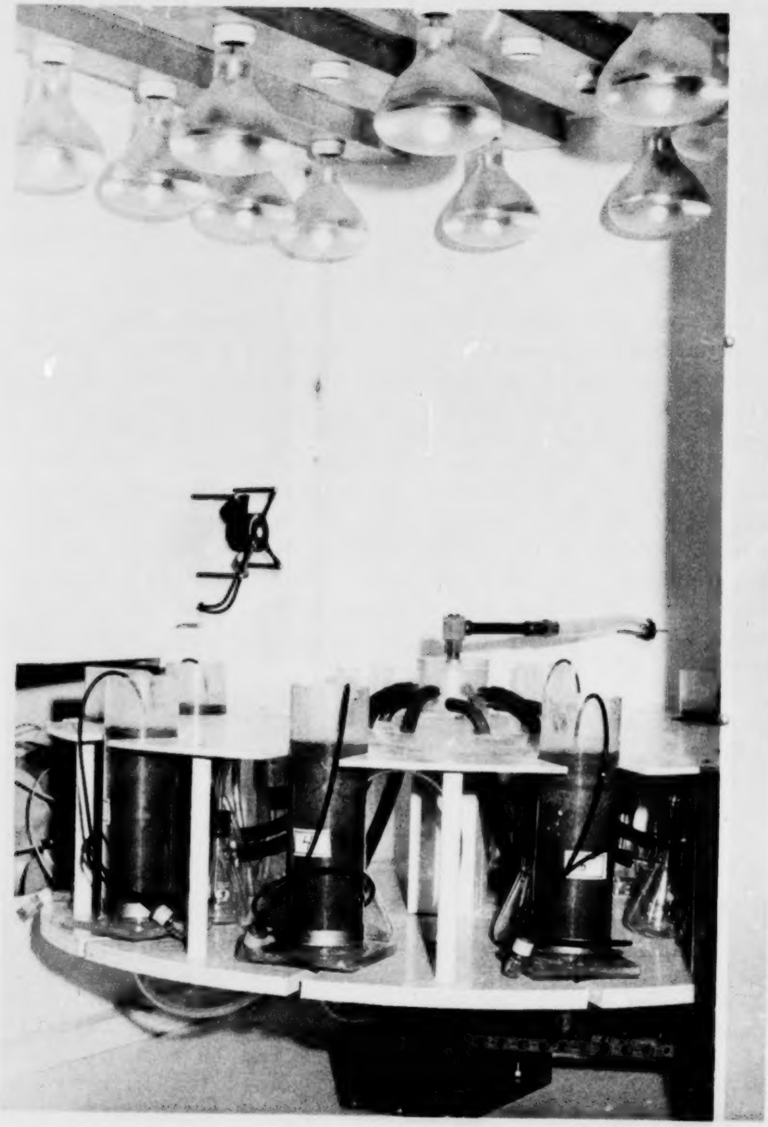

Figure 1. Evaporation Chamber

an additional 40 hours and reweighed. Water lost to drainage was determined by differences in weight of columns following suction and the initial wet weight. Drained columns were then uncovered and exposed to evaporation for about 54 hours, or until at least 25 percent of the remaining soil water was evaporated. Water lost to evaporation was determined by weight. Columns were then re-irrigated and the entire irrigation cycle repeated. The electrical conductivity of the drainage water (EC_{dw}) was measured after each drainage cycle. Conductivity of the soil solution (EC_{sw}), as determined by the salinity sensors, was measured at the end of each evaporation cycle. Drainage was also periodically analyzed for common anions and cations.

RESULTS AND DISCUSSION

The lysimeters were first irrigated in November of 1975. As of August 1, 1976, the columns have been through 48 complete irrigation cycles. Thus, the objective of maximizing irrigation frequency has been met, indicating that the evaporation chamber and associated procedures functioned efficiently. The high evaporative demands generated in the chamber resulted in freewater evaporation rates of 3.7 cm/day. Soil water evaporation rates averaged 0.8 cm/day, and resulted in an average 28 percent loss of available soil moisture, following drainage, in each drying cycle.

The success of the study was dependent on the attainment of relatively constant leaching fractions with each irrigation. Data in Figs. 2,3, and 4 show the variance in actual LF attained, with irrigation number for each of the desired LRs. Data in Fig. 2 for treatment 1 (LR = 0.10) indicate that we achieved an average LF of 0.118 with a standard deviation of only 0.035. Although this average was slightly higher than the desired value of 0.10, the leaching attained was relatively constant throughout the study period and was sufficiently close to the desired value to yield useful data.

The data for treatment 2 (LR = 0.20) are shown in Fig. 3 and also indicate the attainment of a slightly higher, but acceptable, LF that was again reasonably consistent with time. The average LF for treatment 2 was 0.213, with a standard deviation of 0.032.

Data for treatment 3 (LR = 0.40) are given in Fig. 4, and showed the closest agreement between desired and attained LF. This treatment resulted in the largest volume of drainage water which undoubtedly helped to minimize collection and calculation errors. The average LF for treatment 3 was 0.407, with a standard deviation of only 0.027.

The data presented in Figs. 2,3 and 4 represent averages of three soil columns for each leaching treatment. Individual column LFs, however, were just as consistent indicating that our experimental design and procedures were adequate to successfully evaluate the effect of LF on drainage water quality and quantity.

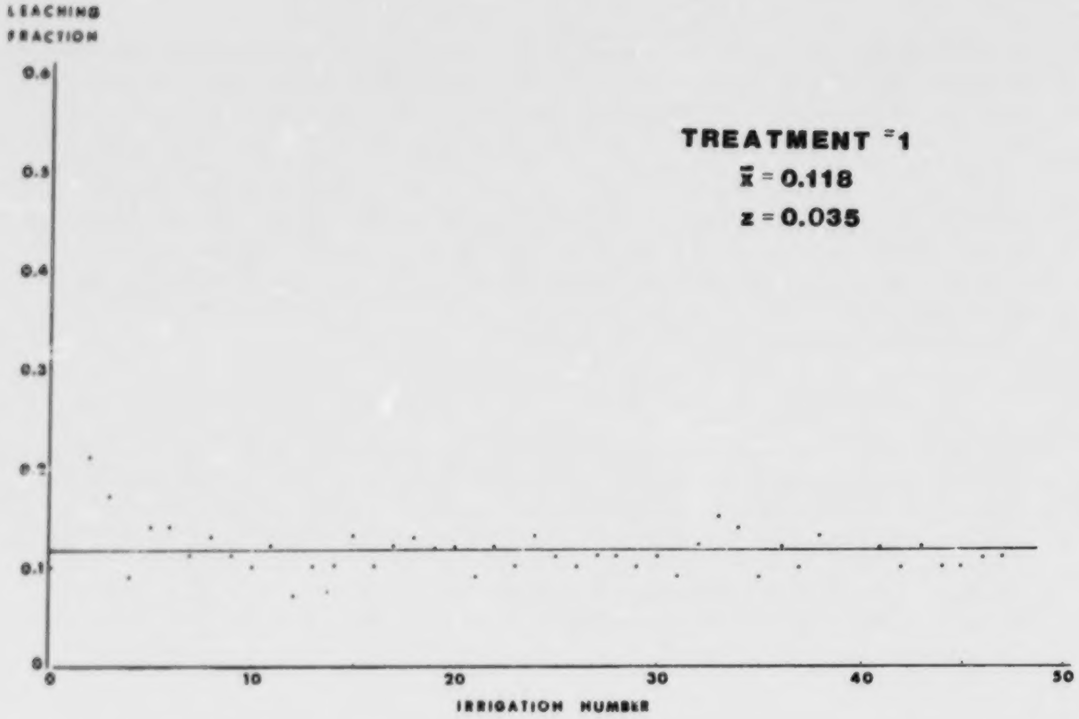

Fig. 2. Variation in the average leaching fraction attained for treatment #1 (LF = 0.10)

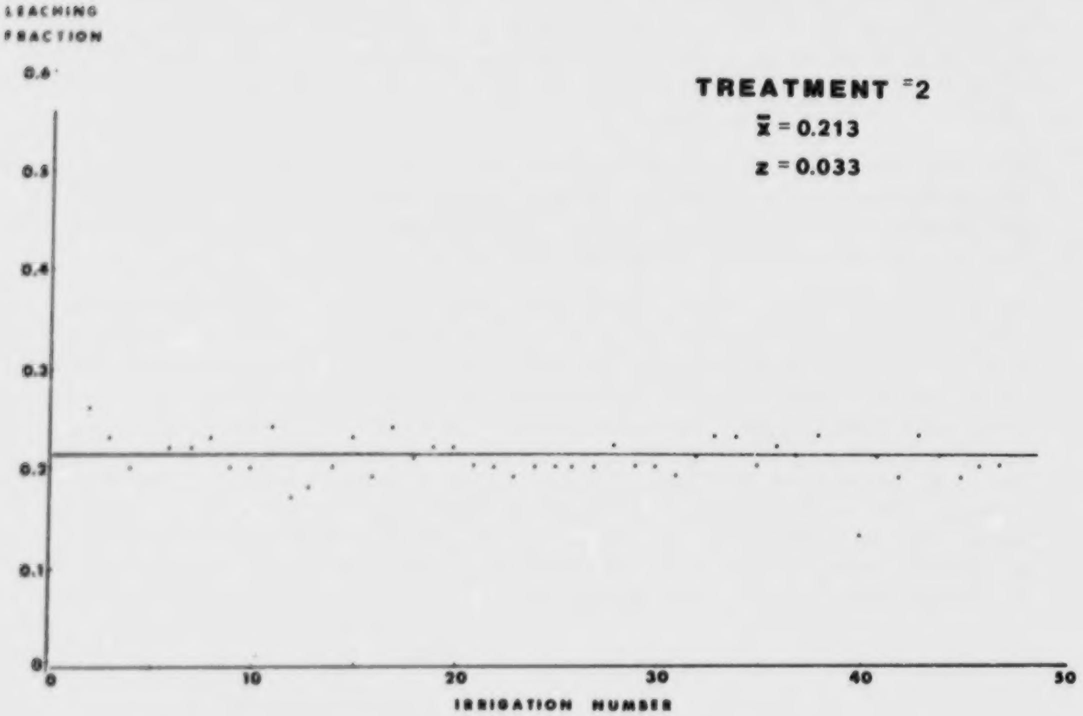

Fig. 3. Variation in the average leaching fraction attained for treatment #2 (LF = 0.20)

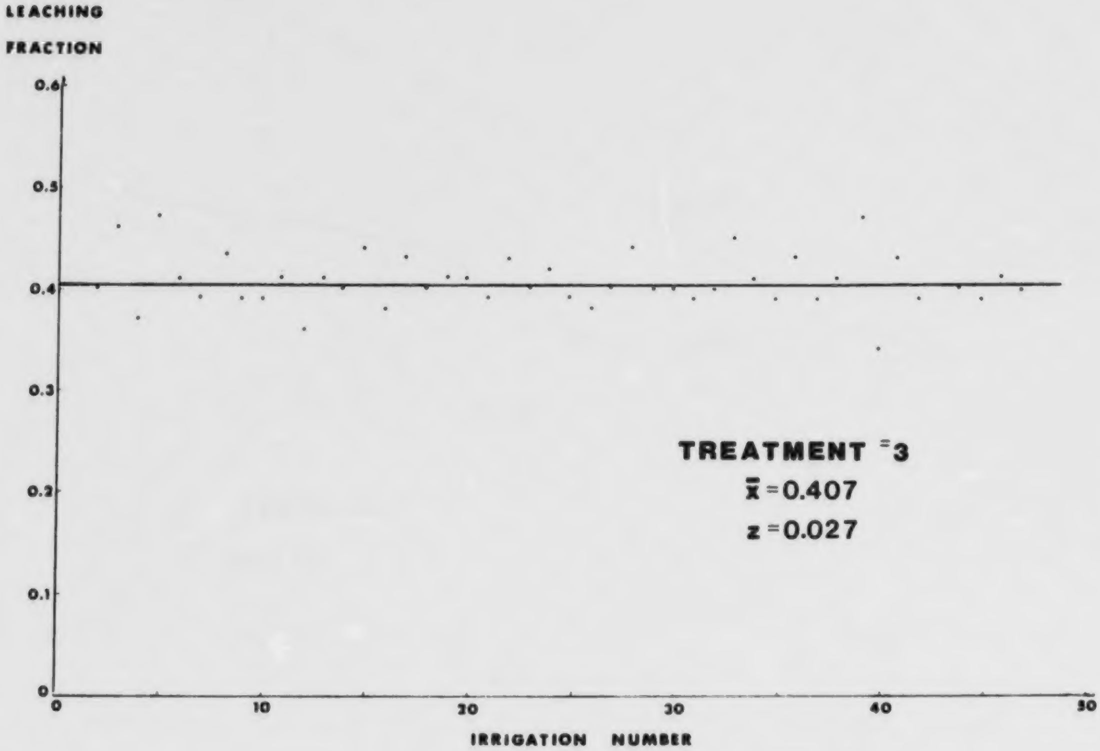

Fig. 4. Variation in the average leaching fraction attained for treatment #3 (LF = 0.40)

Changes in EC_{dw}, EC_{sw} and SAR of drainage water (SAR_{dw}) were monitored for each column on a regular basis. The resulting data were averaged and plotted for each treatment as a function of the irrigation number (Figs. 5,6, and 7).

Data for treatment 1 (LR = 0.10) are shown in Fig. 5. Numbers on the figure, below the EC_{sw} line, indicate the number of pore volumes (1 pore volume = 392 cm^3) of water that had passed through the column just prior to the EC or SAR determinations. Note that after 47 irrigations, only about 1.75 pore volumes of drainage water has been collected; we will have more to say about this point below.

All three indicators of salinity status (EC_{dw}, EC_{sw}, and SAR_{dw}) for the columns of treatment 1 show little evidence of approaching steady-state conditions (Fig. 5). EC_{sw} appears to be approaching a constant value of about 9 mmhos/cm, but EC_{dw} and SAR_{dw} are still steadily increasing even after 47 irrigations. These data may be compared with the data from treatment 2 (Fig. 6) where both EC_{sw} and EC_{dw} have apparently reached steady-state values of 7 and 10 mmhos/cm, respectively. SAR_{dw} for treatment 2, however, is increasing, indicating that chemical changes are still occurring within the column. The continual increase in SAR_{dw} when EC_{dw} has reached a constant value emphasizes the need for care in assessing whether a soil system has reached steady-state.

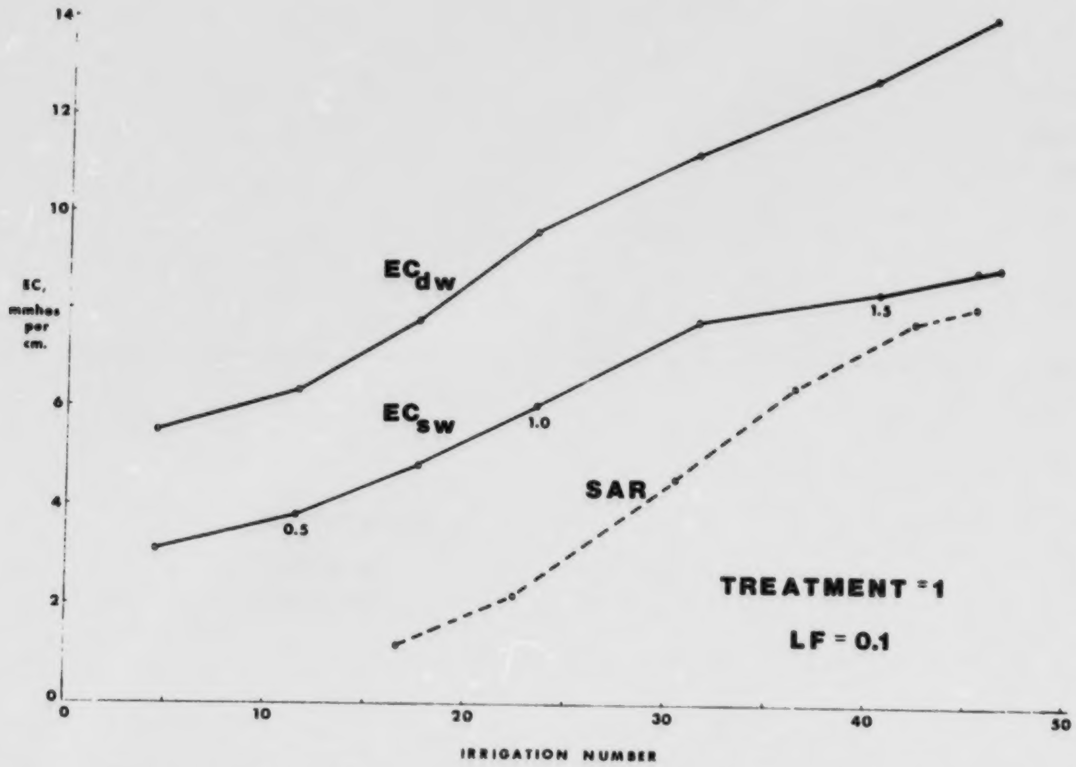

Fig. 5. Changes in average EC_{dw}, EC_{sw}, and SAR_{dw} with irrigation number for treatment #1

Data for the 40 percent leaching treatment (treatment 3) are shown in Fig. 7. Contrary to the data presented in Figs. 5 and 6 for LR of 0.1 and 0.2, respectively, all three measures of column salinity have stabilized after 47 irrigations indicating steady-state conditions. SAR_{dw} approached a constant value much more slowly than either EC_{sw} or EC_{dw}, but apparently stabilized at SAR = 6 after 44-47 irrigations.

As expected, treatment 3 had the greatest volume of drainage water of all the treatments (Fig. 8). After 47 irrigations, the equivalent of about 10 pore volumes (PV) of water had drained from the columns. This can be compared with 4 PV of drainage from treatment 2 (LR = 0.20), and less than 2 PV of drainage in treatment 1 (LR = 0.10). The larger volume of drainage water from treatment 3 no doubt aided in the more rapid attainment of steady-state conditions in this treatment as compared to the lower leaching treatments. Also since reducing LF encourages salt precipitation, changes in soil salinity caused by the treatments are greater in the low leaching treatments. Steady state conditions would thus be expected to be delayed in the lower leaching treatments.

The data in Fig. 7 for treatment 3 can also be used to qualitatively explain why the other two treatments have not reached steady-state. After 2 PV of drainages, both EC_{sw} and EC_{dw} for treatment 3 were still changing rapidly. Thus, treatment 1, which had had only 1.75 PV of drainage collected after 47 irrigations (Fig. 5) would be expected to show rapidly changing EC values even if the magnitude of chemical changes expected were the same in both treatments. Similarly, after 4 PV of drainage, although the EC values had stabilized (Fig. 7), SAR_{dw} continued to climb as was

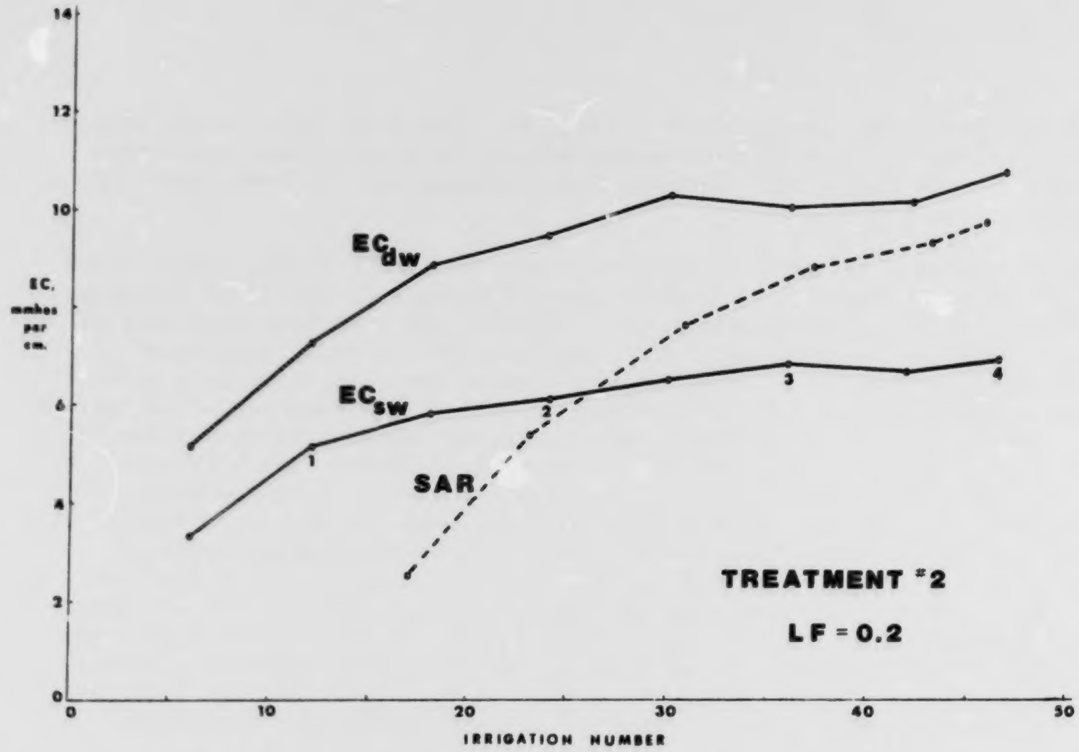

Fig. 6. Changes in average EC_{dw}, EC_{sw}, and SAR_{dw} with irrigation number for treatment #1 .

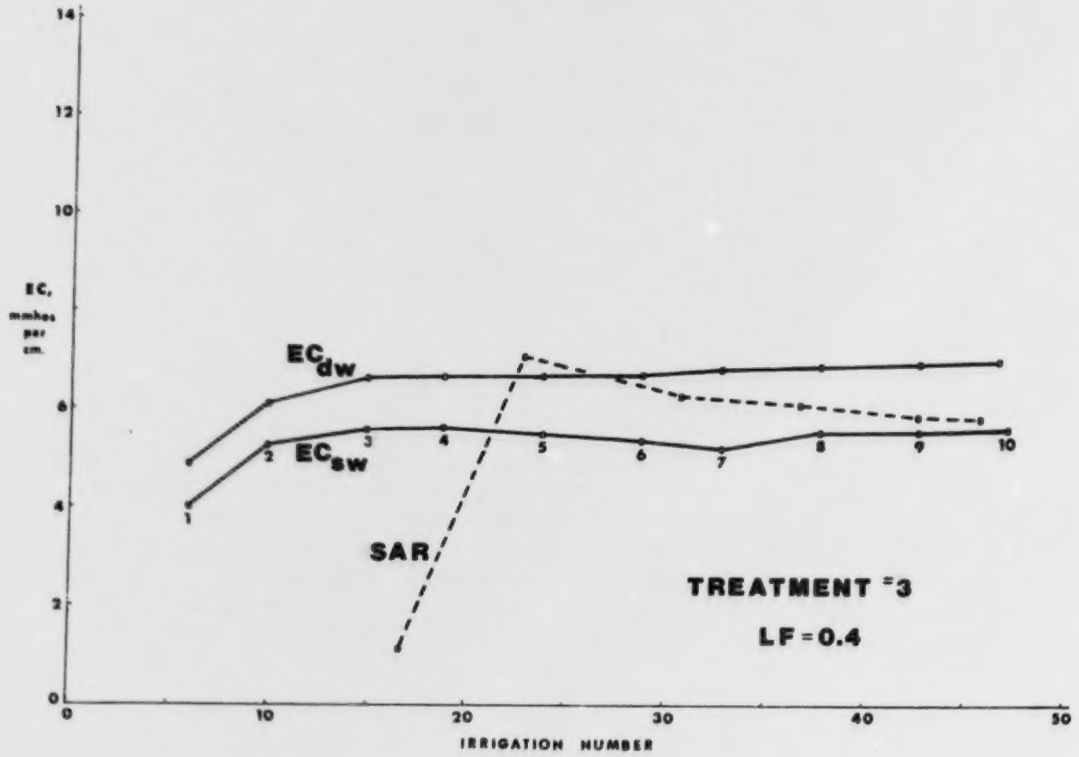

Fig. 7. Changes in average EC_{dw}, EC_{sw}, and SAR_{dw} with irrigation number for treatment #2.

previously shown for treatment 2 (Fig. 6). The study will likely have to continue for several more months before the steady-state conditions indicated in Fig. 7 for treatment 3 are reached for the lower leaching treatments.

Thus, the data we can present to date are limited in final, steady-state comparisons. There are, however, several aspects of minimized leaching effects that can be addressed. For example, one important advantage of the minimized leaching program is the reduction in irrigation water actually applied to a field. Figure 9 shows the cumulative pore volumes of irrigation water applied for each treatment as a function of irrigation number. After 47 irrigations, the 40 percent leaching treatment has had 6 PV more water applied than the 20 percent treatment, and 9 PV more water than was applied in the 10 percent treatment. Drainage water, of course, is similarly reduced (Fig. 8). Expressed in acre-feet (Table 1), the savings in water diverted for irrigation was 1.64 acre-feet/acre when LR was reduced from 0.4 to 0.1. The reduction in return flow was 1.31 acre-feet. Even when LR was reduced from 0.4 to 0.2, the savings in diverted water was 1.06 acre-feet/acre, and in return flow 0.97 acre-feet. In an area where water supplies are dwindling, or where alternate demands for irrigation water are increasing, the water savings possible from instituting minimized leaching could be tremendously important.

Table 1. Predicted (Oster Model) and observed EC and SAR values of drainage water at three different leaching fractions.

	Predicted		Observed	
LF	EC mmhos/cm	SAR (meq/l)$^{1/2}$	EC mmhos/cm	SAR (meq/l)$^{1/2}$
0.4	7.5	6.2	7.0	5.9
0.2	11.7	10.6	10.2	9.8
0.1	19.4	18.6	12.9	8.3

Another aspect of the minimized leaching concept is the influence of the technique on irrigation return flow quality. Since less water is leached through the root zone, the concentration of dissolved salts is higher in the drainage water from lower leaching treatments than from the higher leaching treatments. An important principle in the minimized leaching concept, however, is that the salts are not concentrated in direct proportion to the reduction in leaching water. Such a direct relationship is predicted by the classic leaching requirement equation (Eq. (1)). Depending upon irrigation water quality and LF, salts can be made to precipitate in the soil, thus decreasing the salt burden of drainage water.

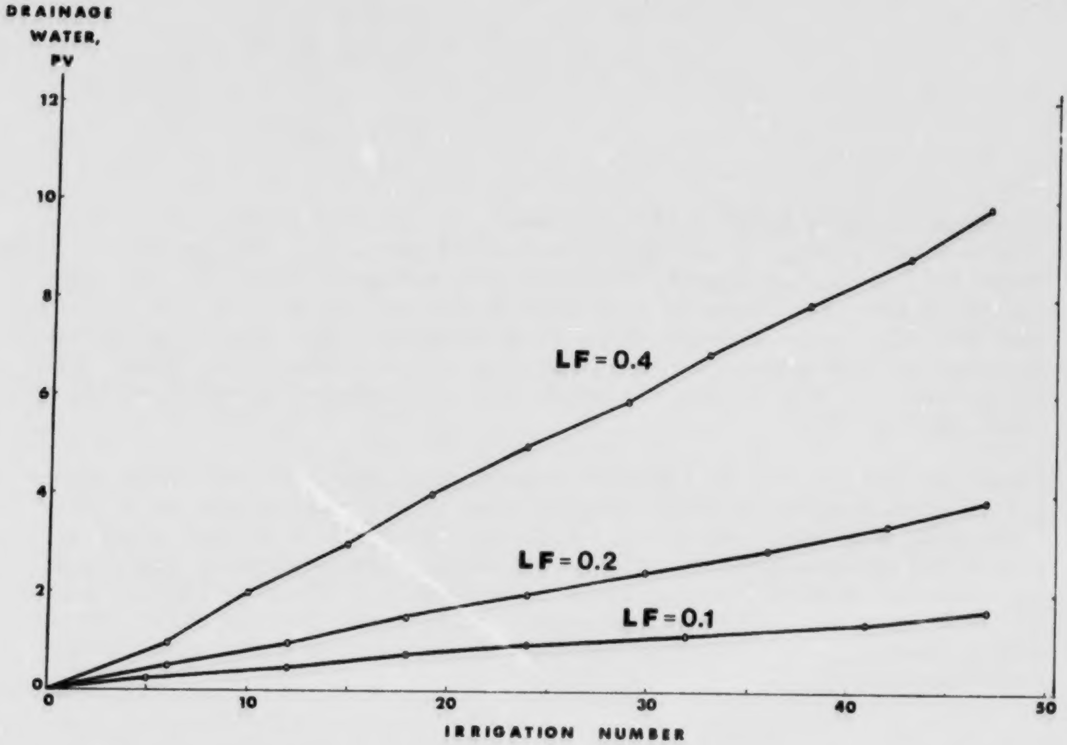

Fig. 8. Cumulative pore volumes of drainage for the three leaching treatments.

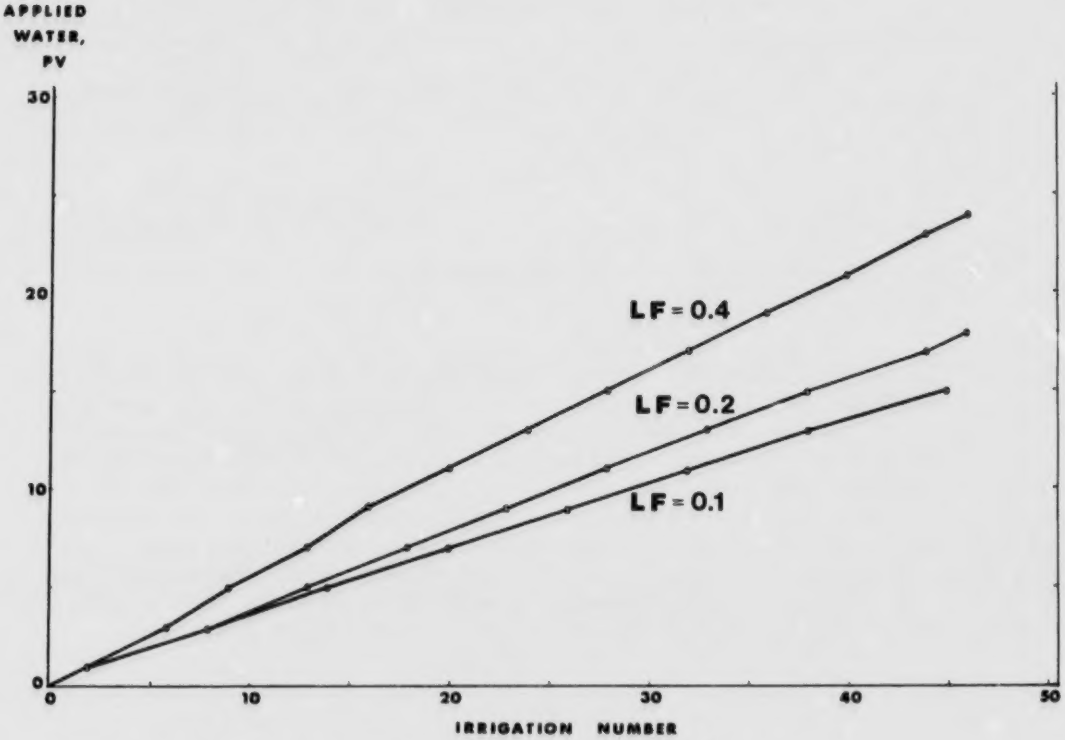

Fig. 9. Cumulative pore volumes of irrigation water applied for the three leaching treatments.

For example, at a LR of 0.41 (treatment 3), and with a EC_{iw} of 3.25 (Pecos River), EC_{dw} is calculated to be 7.9 mmhos/cm. The apparent steady-state EC_{dw} in our treatment 3 was only 7.0 mmhos/cm (Fig. 7). At lower values of LF, the effect is even more dramatic. At a LR of 0.2 (treatment 2), EC_{dw} is calculated to be 15.5 mmhos/cm. Our data (Fig. 6) would indicate an approximate steady-state EC_{dw} of 10.2 mmhos/cm. Thus, both the volume and salt burden of return flow are reduced by reducing the leaching fraction.

Oster and Rhoades (1975) recently described a computer model that predicted steady-state chemical compositions of drainage waters as a function of LF achieved. Since only data for treatment 3 in this study are indicative of steady-state conditions, direct comparisons of predicted and observed results for the three treatments are strictly limited only to the 40 percent leaching treatment. Predictions for the other treatments, however, are useful to indicate expected trends at lower leaching requirements.

Table 2. Effect of leaching fraction on volumes of irrigation water (V_{iw}) applied and drainage water (V_{dw}) received and resultant water savings, acre-feet per acre.

LF	V_{iw}	V_{dw}	"Savings" in Volumes	
			Diversion	Return Flow
0.1	2.55	0.26	0	0
0.2	3.13	0.60	0.58	0.34
0.4	4.19	1.57	1.64	1.31

The data in Table 2 show the steady-state EC_{dw} and SAR_{dw} values obtained in our experiments after 47 irrigations and the same parameters predicted with the Oster model. The data appear to confirm our earlier statements that the 40 percent leaching treatment was at steady-state, that the 20 percent treatment was near, but not at steady-state, and that the 10 percent treatment was far removed from steady-state. The close agreement between predicted and observed results for the 40 percent treatment would also tend to verify the Oster model for the Reagan soil. Adjustments in the model to correct for the elevated temperatures used in this study, however, will have to be made before verification can be completed.

SUMMARY AND CONCLUSIONS

Minimized leaching has been shown to reduce both the volume and salt load of irrigation drainage water from a California soil under lysimeter conditions. The laboratory part of an overall study designed to evaluate minimized leaching with New Mexico soils appears to confirm the California results. Although only the 40 percent leaching treatment has apparently reached steady-state, the 20 percent leaching is sufficiently close to suggest comparable reductions in: 1) irrigation water applied, 2) drainage water collected, and 3) the salt burden of drainage water. Several more months of irrigation are apparently needed to verify the expected results, particularly for the 10 percent leaching treatment. Indeed, the data collected in our artificially maximized irrigation frequency design suggest that steady-state conditions would be obtained in the field only after several seasons of normal irrigation. Even our limited laboratory data, however, suggest that minimized leaching, with its associated water savings, would offer tremendous potential to the farmers of the Pecos Valley.

LITERATURE CITED

Rhoades, J.D., R.D. Ingvalson, J.M. Tucker, and M. Clark. 1973. Salts in irrigation drainage waters: I. Effects of irrigation water composition, leaching fraction, and time of year on the salt composition of irrigation drainage waters. Soil Sci. Soc. Amer. Proc. 37: 770-774.

Rhoades, J.D., J.D. Oster, R.D. Ingvalson, J.M. Tucker, and M. Clark. 1974. Minimizing the salt burdens of irrigation drainage waters. J. Environ. Qual. 3: 311-316.

Oster, J.D. and J.D. Rhoades. 1975. Calculated drainage water compositions and salt burdens resulting from irrigation with river waters in the western United States. J. Environ. Qual. 4: 73-79.

O'Connor, G.A. and C. Cull. 1976. An evaporation chamber with constant suction. Soil Sci. Soc. Amer. J. 40:618-619.

U.S. Salinity Laboratory Staff. 1954. L.A. Richards (ed.), Diagnosis and improvement of saline and alkali soils. U.S.D.A. Handbook 60. 160 pp.

EVALUATING IMPROVED IRRIGATION WATER MANAGEMENT TECHNOLOGIES FOR REDUCING SALT PICKUP FROM GRAND VALLEY

Gaylord V. Skogerboe, Wynn R. Walker,
Robert G. Evans and Stephen W. Smith [1]

INTRODUCTION

In April of 1972, the seven basin states sharing the water resources of the Colorado River Basin (Fig. 1) and the U.S. Environmental Protection Agency (EPA) responsible for the quality of such flows agreed to the necessity of maintaining the concentrations of salts in the Lower Basin at or below existing levels (U.S. Environmental Protection Agency, 1972). Further, the necessity to allow Upper Basin users to proceed with the development of waters apportioned to them under the Colorado River Compact of 1922 was realized. These two segments of the statements emanating from the enforcement conference are, however, contradictory without accompanying each new development with sufficient reductions in existing salt loads to compensate for the effects of the new water use.

The collective decisions regarding the control of salinity in the basin have been induced by the mounting damages incurred by downstream users. Salinity problems are also of international concern owing to the detriments being experienced in the Mexicali Valley of the Republic of Mexico. The methods available for controlling salinity include phreatophyte eradication, reducing evaporation, desalination, elimination of mineralized point sources, importing supplemental water, and improving agricultural, municipal, and industrial water use practices. While certain of these alternatives may be either technologically impractical or politically unacceptable, they represent the array of alternatives from which an overall strategy must be generated. Because of the limited effectiveness of each measure, such a strategy for salinity control must be a combination of several feasible alternatives. The first task is, therefore, to develop the costs and the effectiveness of the individual salinity control measures.

INPUT-OUTPUT ANALYSIS

The increasing salinity problem in the Colorado River Basin has necessitated the collection and analysis of data on water and salt flows in order to evaluate the contributions from various sources. Although several interested governmental agencies have conducted short term studies in the basin, the primary source of data is the stream monitoring system of the U.S. Geological Survey. One of the most comprehensive efforts to summarize

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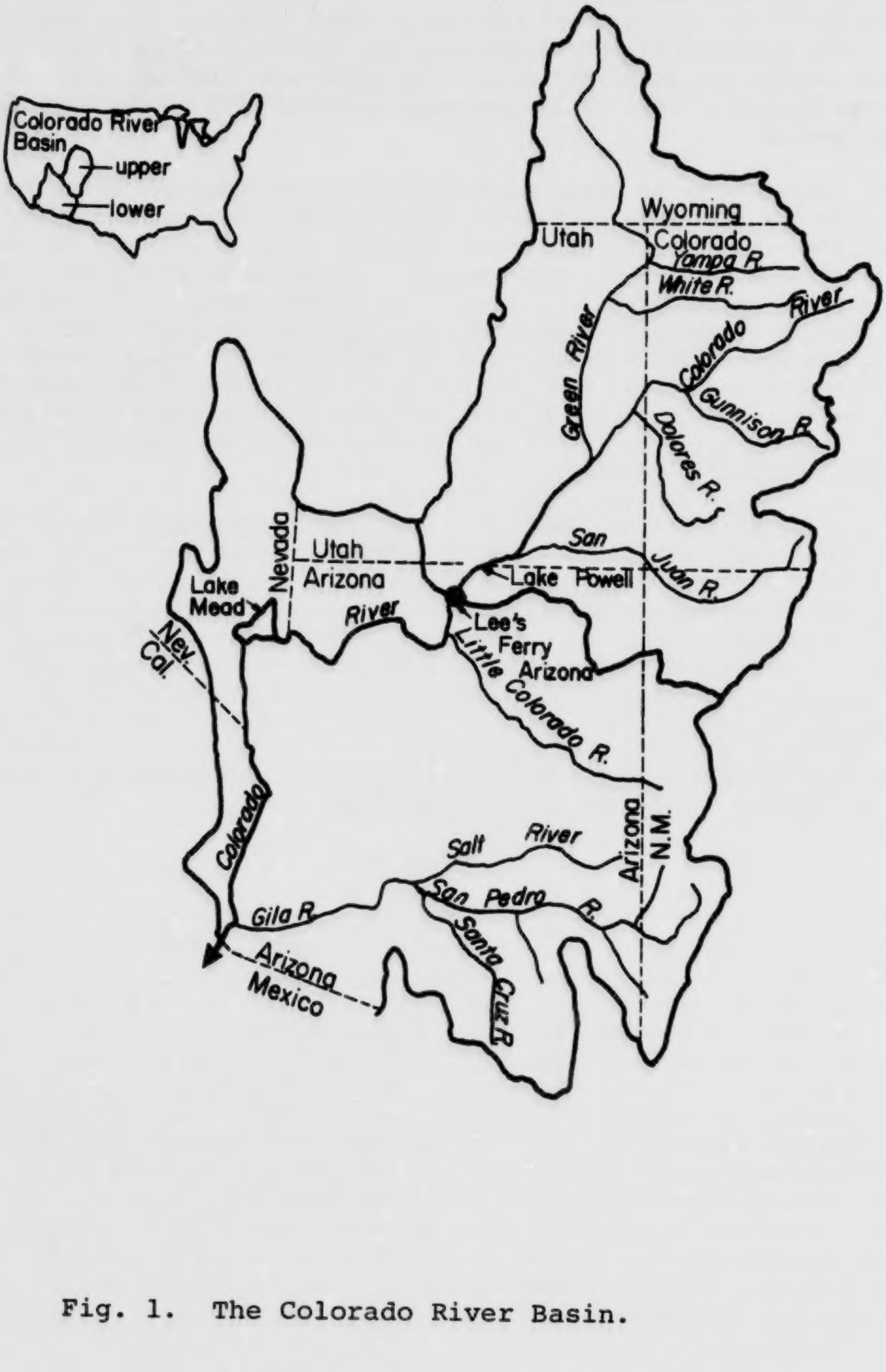
Colorado River Basin
upper
lower
Wyoming
Utah
Colorado
Yampa R.
White R.
River
Colorado
Green River
Gunnison R.
Dolores R.
San
Juan R.
Nevada
Utah
Arizona
Lake Powell
Lake Mead
River
Lee's Ferry
Arizona
Little Colorado R.
Nev.
Cal.
Colorado
Salt River
Arizona
N.M.
San Pedro R.
Gila R.
Santa Cruz R.
Arizona
Mexico

Fig. 1. The Colorado River Basin.

and analyze these data was made by Iorns, Hembree, and Oakland (1965) for the period between 1914 and 1957 and adjusted to the 1957 conditions. The study was inclusive of the entire Upper Colorado River Basin, but for the purposes of this paper only the section dealing with the Grand Valley area has been extracted. The total salt loading to the Colorado River from the Grand Valley averaged about 680,000 metric tons during the period.

The 1963-1967 water years were selected by the Colorado River Board of California (1970), in conjunction with various governmental agencies, to appraise the salinity sources in the basin and to evaluate the future impact of water resource developments on mineral water quality. The results pertaining to the Grand Valley in particular indicated the salt pickup to be about 18 metric tons per hectare per year, which is the results Hyatt (1970) established for the 1963-1968 years. Both of these references are useful data sources for examination of the Upper Colorado River System. Also both studies utilized salinity data collected by the Federal Water Pollution Control Administration (now the U.S. Environmental Protection Agency).

One examination of the sources of salinity in the basin reveals that of man-made contributions, irrigated agriculture has the largest effect. Consequently, the major aspect of salinity control in the region must be the effective use of irrigation diversions by improving the efficiency of conveyance, farm, and wastewater systems. One of the several important efforts funded by the U.S. Environmental Protection Agency to develop salinity control technology is the Grand Valley Salinity Control Demonstration Project in western Colorado (Fig. 2). The reason for selecting Grand Valley for intensive study is because the annual salt pickup per acre is greater in this particular irrigated area than any other irrigation system in the Upper Basin.

STUDY AREA

The Colorado River enters the Grand Valley from the East, is joined by the Gunnison River at Grand Junction, Colorado, and then exits to the West. The contribution to the total salt flows in the basin from this area, illustrated in Fig. 3, is highly significant. The primary source of salinity is from the extremely saline aquifers overlying the marine deposited Mancos shale formation. The shale is characterized by lenses of salt in the formation which are dissolved by water from excessive irrigation and conveyance seepage losses when it comes in contact with the Mancos shale formation. The introduction of water through these surface sources percolates into the shallow groundwater reservoir where the hydraulic gradients it produced displace some water into the river. This displaced water has usually had sufficient time to reach chemical equilibrium with the salt concentrations of the soils and shale. These factors also make the Grand Valley an important study area, since the conditions encountered in the valley are common to many locations in the basin.

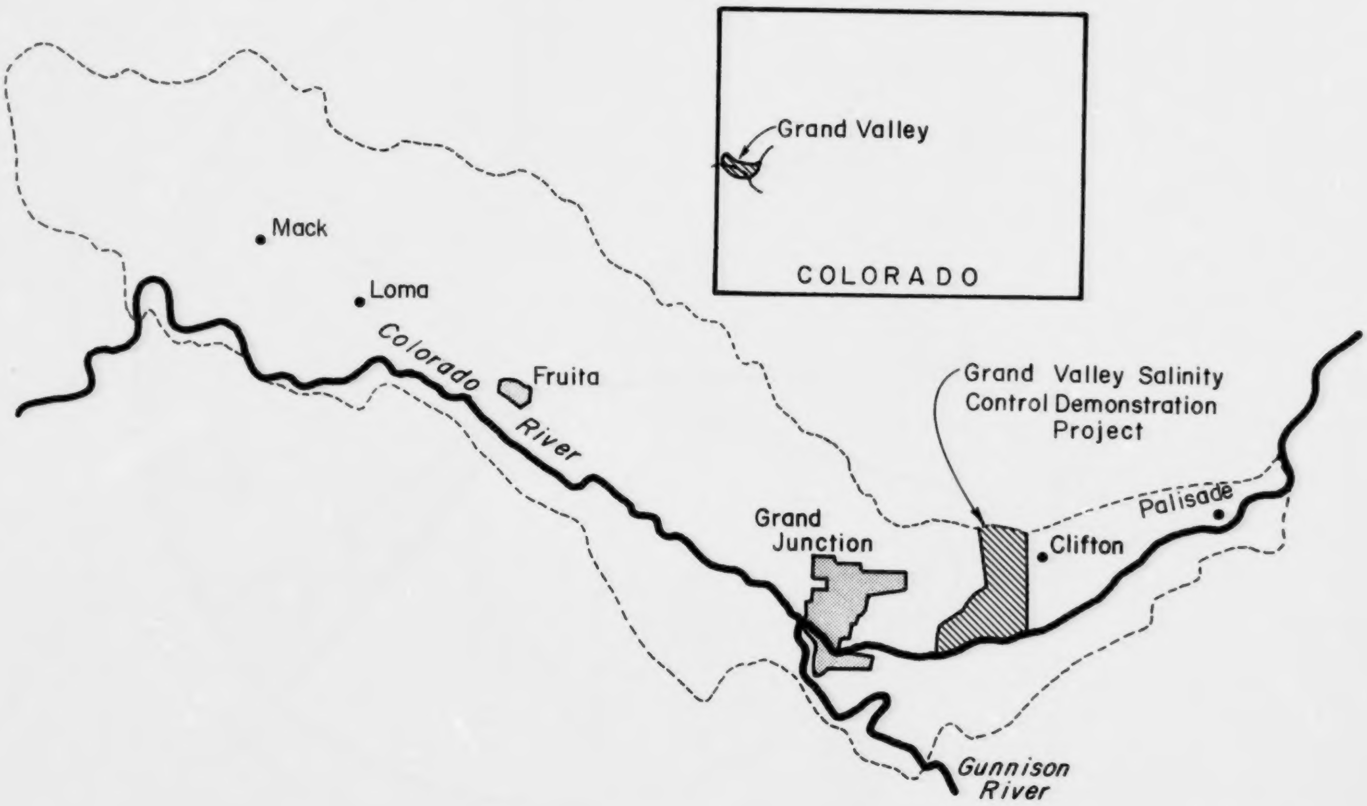
Grand Valley
COLORADO
Mack
Loma
Colorado River
Fruita
Grand Junction
Grand Valley Salinity Control Demonstration Project
Clifton
Palisade
Gunnison River

Figure 2. The Setting of the Grand Valley showing the location of the project area.

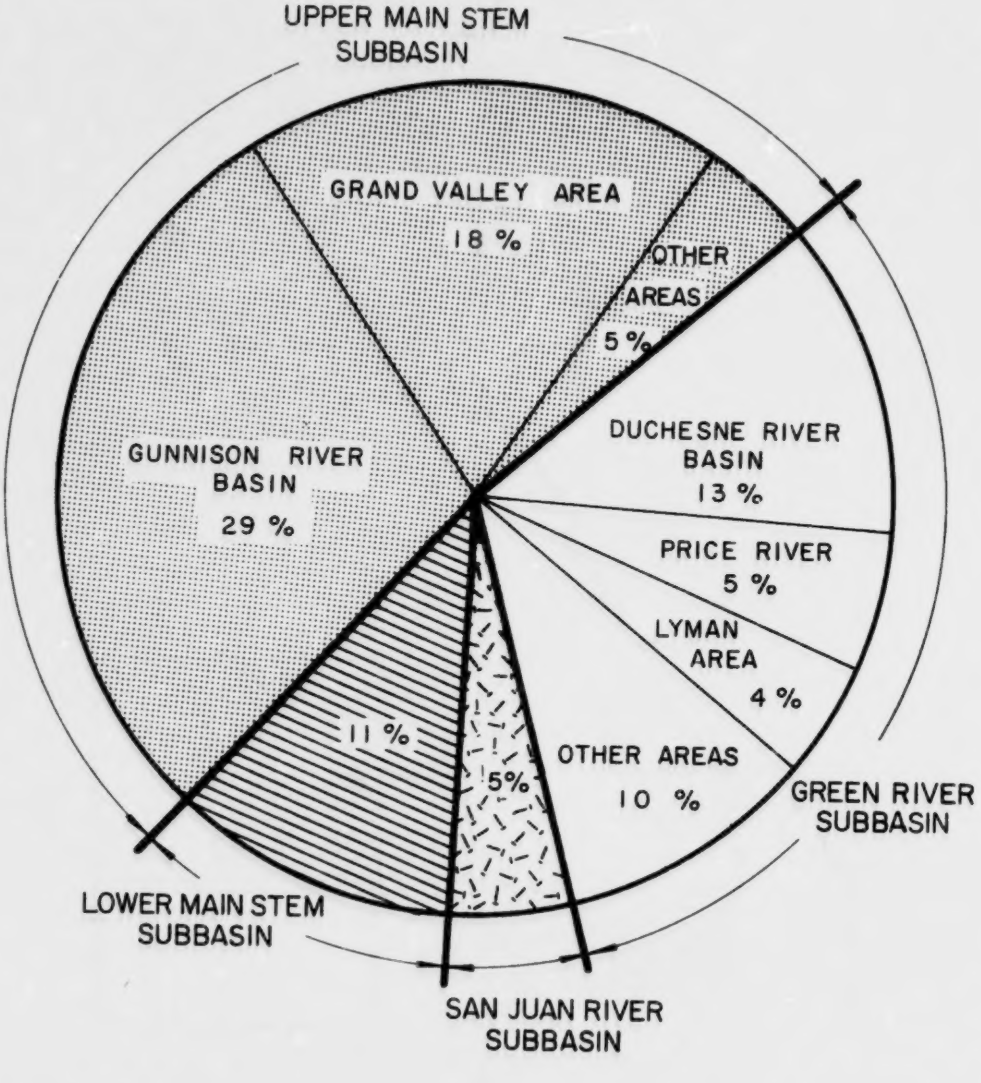

Fig. 3. Relative magnitude of agricultural salt sources in the Colorado River Basin (U.S. Environmental Protection Agency, 1971).

The study area, shown in Fig. 4, was chosen as an intensive study area in which the bulk of the investigation was to be conducted and also includes most of the construction and demonstration efforts. This area was designated for detailed investigations regarding various salinity control measures on the water and salt flow systems in an irrigated area. The intensive study area was selected for its accessibility in isolating most of the important hydrologic parameters, but had the important advantage that it allowed five irrigation companies to participate in one unit.

HYDRO-SALINITY MODEL

In undertaking the Grand Valley Salinity Control Demonstration Project, one of the first tasks was to conceptualize a hydro-salinity model of the intensive study area. This model had to have sufficient sensitivity to detect the effects of various salinity control measures upon the salt pickup reaching the Colorado River. Then, the model could be used to design the field data collection system. Finally, the model could be used to extrapolate results from the intensive study area to the entire Grand Valley.

A difficulty often encountered while preparing water and salt budgets is the variability in the accuracy and reliability with which the hydrologic and salinity parameters are measured. Usually, the measurement precision varies with the scope of the research and the area of the study. The intensive study area on this project has been observed in great detail.

Since the hydrologic system is difficult to monitor and predict, it is impractical to expect their models to operate without applying some adjustments in order that all components will be in balance. In short, the budgeting procedure is usually the adjustment of the segments in the water and salt flows according to a weighting of the most reliable data until all parameters represent the closest approximation of the area that can be achieved with the input data being used. The vast and lengthy computation procedure of calculating budgets is facilitated by a mathematical model programmed for a digital computer. A complete listing and explanation for its operation has been previously reported (Walker, 1970). For the purposes of this paper, the more important aspects will be extracted for discussion. A schematic diagram of a general hydro-salinity model is shown in Fig. 5.

The model of the intensive study area was developed in three general sections:

1. All diversions from the canals through small turnouts into the lateral network are distributed onto the farmland after taking into account lateral seepage losses;

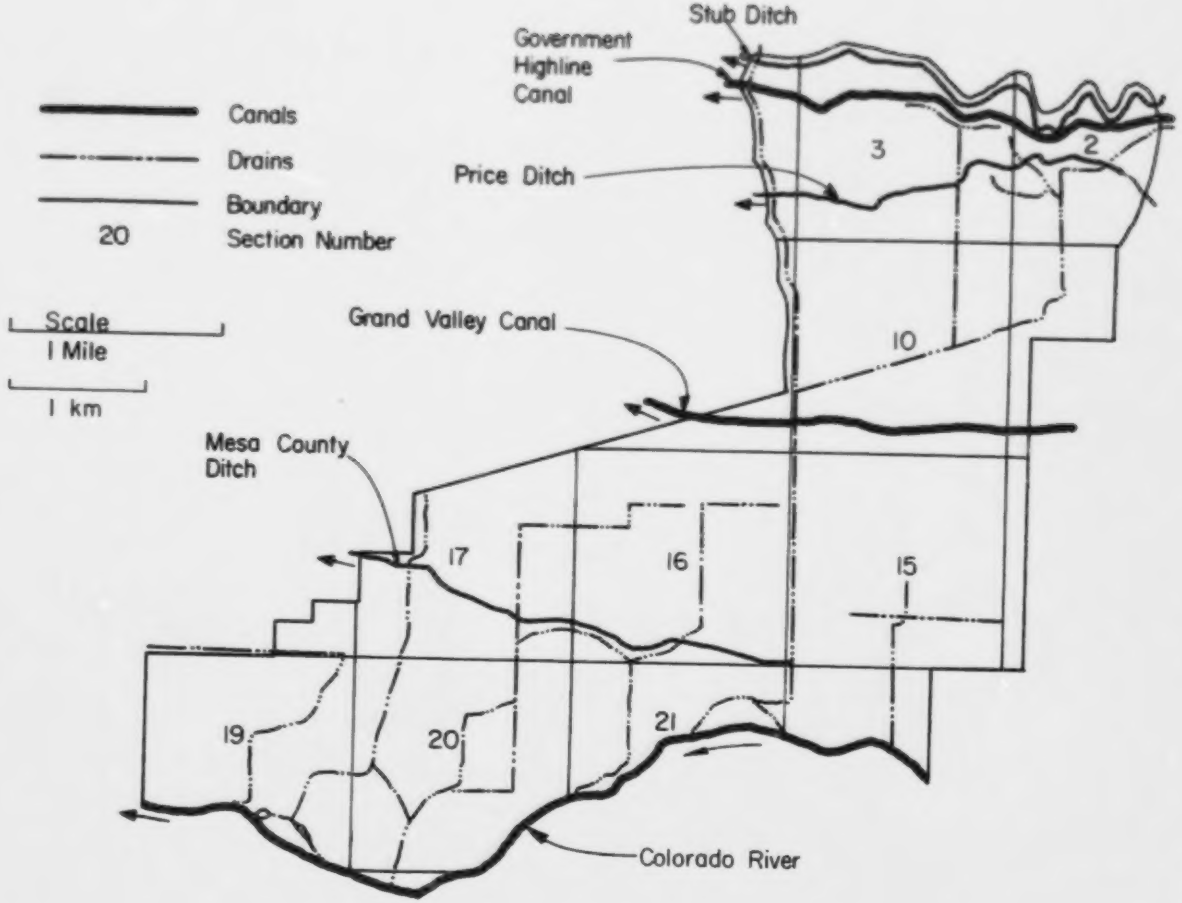
Canals
Drains
Boundary
20 Section Number
Scale
1 Mile
1 km
Stub Ditch
Government Highline Canal
Price Ditch
Grand Valley Canal
Mesa County Ditch
Colorado River
2
3
10
15
16
17
19
20
21

Fig. 4. Intensive study area, Area I, of the Grand Valley Project.

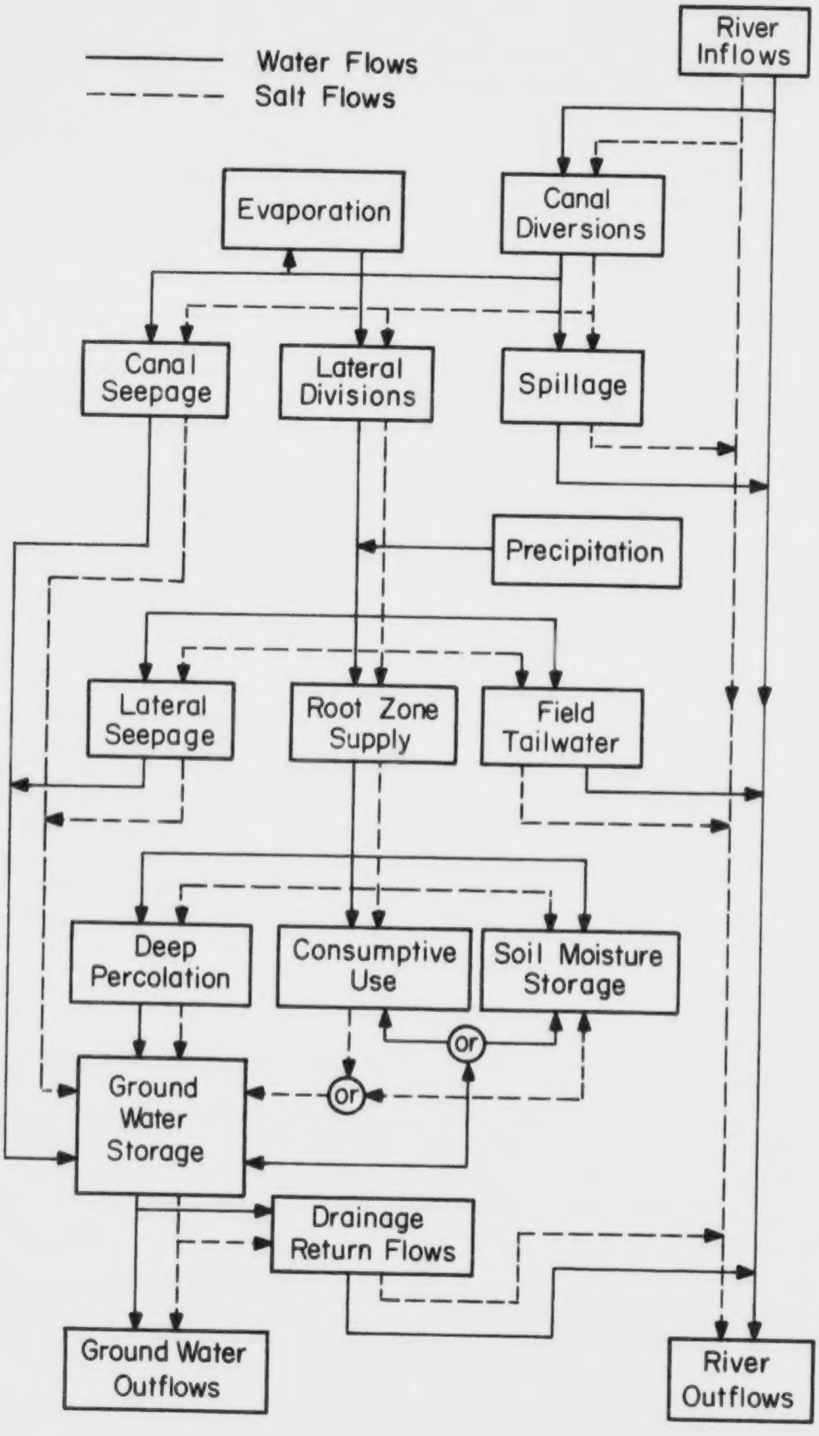
Water Flows
Salt Flows
River Inflows
Canal Diversions
Evaporation
Canal Seepage
Lateral Divisions
Spillage
Precipitation
Lateral Seepage
Root Zone Supply
Field Tailwater
Deep Percolation
Consumptive Use
Soil Moisture Storage
or
or
Ground Water Storage
Drainage Return Flows
Ground Water Outflows
River Outflows

Fig. 5. Schematic generalized hydro-salinity model.

2. Flow within the root zone including evapotranspiration, tailwater runoff, and deep percolation losses; and

3. Groundwater return flows resulting from seepage and deep percolation return to the river system with their large salt loads through both surface and subsurface drainage routes.

Cropland Diversions

The irrigation supply is diverted from the Colorado River by means of large check-type dams and then conveyed through the Grand Valley, with water being lost by seepage, spilled into wasteways, evaporated, and discharged through turnout structures into laterals. Two of these alternate routes, spillage and the lateral diversions, will be examined further.

Natural washes and drains located throughout the valley serve as wasteways for canal regulation operation. The Grand Valley Canal dumps water into Lewis Wash to supply the Mesa County Ditch. These flows are mixed with a considerable drainage flow and a noticeable water quality degradation occurs.

Diversions into the lateral system in the test area are also reduced by seepage. Evaporation is insignificant. Most of these small conveyance channels carry less than 0.14 m^3/sec but may serve as many as 100 farmers. Both maintenance and management of laterals below the canal turnout is poor. Of the flows reaching the cropland, only about 60 to 70 percent of the water actually enters the root zone and the remaining flow is field tailwater and returns directly to the river via the open drainage system. Comparison of drainage discharges throughout three irrigation seasons indicated that about 80 percent of the surface drain flows are field tailwater.

Root Zone Flows

The goal of an irrigation is to recharge the soil moisture reservoir with sufficient water to meet the growing crops needs until the next irrigation, as well as to maintain an acceptable salt concentration in the root zone. The tendency to over-irrigate has produced high water tables and salinity problems. The purpose of the root zone submodel was to separate the various flows occurring within the root zone in sufficient detail to quantify the salinity problem.

The important water movements within the root zone are evapotranspiration and deep percolation, with water storage changes also occurring. The separation of these flows by measurement is impractical on a large scale. Consequently, empirical computational methods are employed. The model developed for this study accounts for these basic water and salt flows only by a budgeting process. The assumptions made regarding the operation of this model include that the diversions are applied uniformly over each acre of cropland. Phreatophyte vegetation in the area was assumed to extract water only from the groundwater flows or to use only precipitation entering the root zone of these plants.

Several applicable methods of estimating evapotranspiration could have been used in this study. However, because the shortest time period employed in the study was one month, the Blaney-Criddle Method provided an acceptable degree of accuracy. This method determines consumptive use as a function of mean monthly temperature and the percentage of daylight hours occurring during the month. As the study progressed, a comparison was made between the Blaney-Criddle Method and some of the more sophisticated energy balance relationships. Comparisons indicated that the Blaney-Criddle Method was somewhat conservative.

With the evapotranspiration data and field measurements of moisture holding capacity, texture, infiltration rates, and rooting depths, the budgeting scheme proceeded with computation of deep percolation losses from the root zone. The calculations were initiated by assuming that the crops use soil moisture at the potential rate until the wilting point is reached. The calculated potential use is then limited to the water added by irrigation and the existing available soil moisture storage. If the supply to the root zone from irrigation is insufficient to meet the crop demands, but the available soil moisture storage is sufficient to make up the difference, then the crop demand is satisfied. It was assumed that while the soil moisture reservoir is below field capacity, no deep percolation occurs. If the total available moisture in a period is insufficient to meet the total demand, the crops use all water available. A term called "consumptive use deficit" is defined as the difference between the potential and actual uses. Deep percolation losses and leaching occur when the supply is more than enough to meet the crop demands and fill the soil moisture reservoir to field capacity.

The salts in the applied water move with the water into the root zone where they are concentrated by the evapotranspiration process. The behavior of specific ions is complex and has not been considered in this particular study. However, additional research is underway in the Grand Valley to provide prediction equations for specific ions. The assumption has been made that the salts acquired from the intensive study area occur as salt pickup below the root zone. This assumption allows for a simplified computational procedure in evaluating the demonstration area based upon an input-output model.

Groundwater Model

Most of the water in the soils and aquifers in the test area originate as seepage from canals and laterals, as well as deep percolation from the irrigation of croplands. The groundwater discharges eventually reach the river as surface drainage interception or subsurface return flows. The flows in the surface drainage system were measured by installing flow measuring devices at the outflow points. The subsurface return flows were not measured but were estimated from water table elevation data and the hydraulic gradients in the aquifers. Considerable effort was made to evaluate the necessary parameters to use in the groundwater computations. For purposes of this study, Darcy's steady state equation was used (Luthin, 1966)

$$Q = AK \frac{dh}{dk} \qquad (1)$$

in which Q is the discharge, A is the cross-sectional area of flow, K is the hydraulic conductivity, and dh/dk is the hydraulic gradient in the direction of flow.

The groundwater analysis begins by comparing the values for subsurface return flow obtained from a mass balance of the area to the values obtained by calculation using the field data. It was possible to formulate two estimates of the subsurface return flows and then by adjusting the model until both methods yielded the same values, a satisfactory alignment between the hydrologic and salinity parameters was obtained. Because the model only focuses attention on the relative magnitude of hydraulic conductivities, the cross-sectional areas of the strata need only be in proper proportion with respect to depth, and the width can be any convenient value. Then, the values for cross-sectional area can be adjusted with the known hydraulic conductivities. The model adjusts the values of strata hydraulic conductivity until both estimates of the flows are equal. Since this is done on a monthly basis, the model calculates twelve values of hydraulic conductivity for each strata for each year. When adjustments in the model finally result in homogeneous values of hydraulic conductivity, the model represents the "best fit" between monitored and estimated data.

The groundwater modeling procedure can also be described mathematically. The form of Eq. 1 for a number of strata can be written,

$$Q = \sum_{i=1}^{n} A_i K_i{}' \frac{dh_i}{dx_i} \qquad (2)$$

where A_i is the cross-sectional area of the i^{th} strata, K_i' is the actual measured conductivity of the i^{th} strata, and dh_i/dx_i is the gradient in the flow direction acting on the i^{th} strata. The value obtained from Eq. 2 is then used to adjust the model values of hydraulic conductivity,

$$K_i = \frac{TGWOF}{Q} \; K_i \qquad (3)$$

where K_i is an adjusted hydraulic conductivity encompassing adjustments for units and strata areas, Q is the value obtained in Eq. 2, and TGWOF is the subsurface return flow estimate from the mass balance analysis.

Summary of Model Results

In this section, a summary of the input-output analysis and results from the hydro-salinity model will be presented. Inflows to the Grand Valley occur as flows in the Colorado River, Gunnison River, and precipitation. In addition, a small quantity of water is imported for domestic and industrial purposes, and a possibility exists that precipitation on the watershed adjacent to the valley may contribute via diffuse groundwater inflows. Neither of these latter flows are deemed significant, especially the inflow from surrounding lands because of the low annual precipitation (200-250 mm) and high evaporative demands (1000-1100 mm).

As a means of better identification, data for the 1968 water year from the U.S. Geological Survey (USGS) and U.S. Weather Bureau can be utilized. Inflows passing the USGS gaging stations "Colorado River near Cameo" (297,523 ha-m), "Plateau Creek near Cameo" (13,810 ha-m), and "Gunnison River near Grand Junction" (178,045 ha-m) totaled 489,378 ha-m carrying an estimated salt load of 2,787,400 metric tons. The outflows passing the station "Colorado River at Colo-Utah State Line" totaled 458,923 ha-m and approximately 3,423,314 metric tons of salt. These figures represent either published data or interpolations thereof. It should be noted that the state line station collects only limited quality data.

A comparison of the inflows and outflows indicates that 30,458 ha-m of water were depleted from the system and 635,914 metric tons of salt added. Precipitation records indicate that approximately 9,248 ha-m fell on the land encompassed by the irrigated boundaries, of which it is estimated that one-third could be classed as "effective on the irrigated acreages." These estimates are congruent with similar computations presented by Iorns et al. (1965), Hyatt (1970) and U.S. Environmental Protection Agency (1971).

Another check on these numbers can be made from land use data collected by Walker and Skogerboe (1971). A somewhat more definitive breakdown is presented in Table 1. Westesen (1974) estimated that the consumptive use based on the pan evaporation data from the U.S. Weather Bureau and calculations using the Modified Jensen-Haise method amounted to about 36,374 ha-m annually, including almost 3,083 ha-m of effective precipitation on other vegetative uses. Thus, the inflow-outflow data for this particular year regarding water flow is acceptable. An examination of the salt flows will be noted for comparison in the following paragraphs.

The second approach to establishing the effects of water use in the Grand Valley is to model the complex interrelationships associated with irrigation and drainage. Several parameters are added to the analysis to account for the various flows which take place.

The first segment encountered is the delineation of the canal diversions. As the water is diverted from the rivers into the canals and ditches, a certain portion of the flow seeps or evaporates from the conveyance

Table 1. Agricultural land use in the Grand Valley.

Land Use	Area (ha)	Percent of Total
Irrigated	24,624	53
Idle	3,928	8.5
Dwelling & Premises	4,321	9.3
Open Water	688	1.5
Phreatophyte	6,141	13.2
Natural Terrain	6,721	14.5
Total[1]	46,423	100.0

[1] Roads and railways have been omitted.

Table 2. Grand Valley water budget for 1968 water year.

Budget Item	hectare-meters
Surface Inflows	
Colorado River near Cameo, Colorado	297,523
Plateau Creek near Cameo, Colorado	13,810
Gunnison River near Grand Junction, Colo.	178,045
Total	489,378
Effective Precipitation	
Cropland	3,083
Phreatophytes	666
Total	3,749
System Depletions	
Water Surface Evaporation	
Canals	986
Rivers	987
Phreatophyte Consumption	
Along Canals and Drains	7,891
Adjacent to Rivers	2,639
Cropland Consumption	21,701
Total	34,204
Surface Outflows	
Colorado River at Colorado-Utah State Line	458,923

surfaces, while still another fraction is spilled into wasteways as a means of regulating capacity. The remainder of the flow is diverted through small headgates into an extensive lateral system leading to the fields. It is important in this type of analysis that each flow path be defined, because each results in a different salinity effect. For example, the evaporative losses concentrate the salts in the remaining flows, whereas the seepage enters the saline groundwater basin and results in salt pickup.

Lateral diversions eventually become seepage, field tailwater, root zone additions, or evaporations, as was the case above. In a similar manner, the root zone additions result in cropland consumptive use or deep percolation. When deep percolation is combined with seepage losses, a groundwater flow segment is begun which results in the severe salt loadings common in the valley. A great deal of the groundwater is consumed by water-loving phreatophytes abundant in the area and some of the flows are intercepted by the open-ditch drainage system. A substantial amount returns to the rivers through aquifers making precise measurement difficult.

Westesen (1974) examined the 1968 water year in some detail and combined many of the principles discussed by Walker (1970) into an accounting of the flows derived for irrigation in the Grand Valley. His results, shown in Tables 2, 3, and 4, compare very well with data collected by the authors in recent years.

Much of the local water table problems are due to over-irrigation, especially along the higher northern lands in the area. Lower areas and isolated trouble spots are affected by excessive groundwater flows trying to leave the area. If the local canals and laterals were lined (including farm head ditches), Table 4 indicates that 9,494 ha-m annually, which amounts to 55% of the groundwater inputs, would be prevented from contributing to local drainage problems (if only the canals were lined the groundwater would be decreased by only 18%). Such improvements may also reduce the evapotranspiration from phreatophytes and result in significant water savings as well. Canal lining appears to be the initial program for controlling salinity in the Grand Valley although it is the least effective alternative available.

Probably the greatest potential for salinity control lies in on-farm water management which directly includes the lateral conveyance system. Together, deep percolation and lateral seepage contribute 85% of the groundwater flows. If effective irrigation scheduling programs are incorporated locally, which means accompanying the scheduling services with rehabilitation of the irrigation systems, the need for field drainage will be diminished.

Thus, the first steps in a salinity control program are to minimize: (a) deep percolation losses from croplands (ideally, the deep percolation losses would not exceed the leaching requirement); (b) seepage losses

Table 3. Grand Valley distribution of canal flows in 1968.

Budget Item	hectare-meters		hectare-meters
Canal Diversions	69,048		
Spillage			12,699
Seepage			3,083
Evaporation			987
Lateral Diversions			52,279
		TOTAL	69,048
Lateral Diversions	52,279		
Seepage			6,288
Field Tailwater			19,975
Root Zone Diversions			26,016
		TOTAL	52,279
Root Zone Diversions	26,016		
Evapotranspiration			18,495
Deep Percolation			7,521
		TOTAL	26,016
Groundwater Return Flows	16,892		
Phreatophyte Consumption			7,398
Subsurface and Drain Flows			9,494
		TOTAL	16,892

Table 4. Salt budget for Grand Valley during 1968.

Budget Item	Flow (ha-m)	Concentration (mg/ℓ)	Salt Load (metric tons)
Inflows			
Colorado River near Cameo	297,523	454	1,352,622
Plateau Creek near Cameo	13,810	454	62,638
Gunnison River near Grand Junction	178,045	769	1,372,140
		TOTAL	2,787,400
Outflows			
Colorado River near Colo-Utah State Line	458,923	745	3,423,314
Salt Pickup			635,914

from canals and laterals. By minimizing the amount of moisture reaching the groundwater, the requirements for field drainage will also be minimized. As higher levels of salinity reduction are sought, field drainage becomes a more feasible component of a valley-wide salinity control program.

The results to date clearly show that the key to reducing the salt load contribution to the Colorado River from Grand Valley is improving on-farm water management practices in order to minimize deep percolation losses and consequent salt pickup.

PREDICTING CHEMICAL QUALITY

The hydro-salinity model describes the present situation in the study area regarding water and salt flows. However, the only method for predicting the reduction in salts returning to the river through implementation of any salinity control measure(s) is by assuming a one-to-one relationship between water and salt. That is, if the subsurface return flow is reduced by 50%, the salt is also reduced by 50%. In order to overcome this limitation, a project "Irrigation Practices, Return Flow Salinity, and Crop Yields" was initiated.

Three adjacent fields containing 9.3 hectares were leased for this study. The area has been divided into 54 plots which are 30.5 meters by 30.5 meters in size, two plots which are 12.2 meters by 61 meters, two plots which are 12.2 meters by 91.4 meters, and five plots which are 12.2 meters by 152 meters. Each plot is used for a different replication of the crop, fertilizer and irrigation treatments. They have been constructed so that each plot performs as a large lysimeter. A trench was excavated slightly into the shale along the lines dividing the plots. A plastic curtain was then placed vertically in the center of the trench to divide the individual plots. The lower edge of the curtain is "sealed" to the shale by backfilling to the original elevation of the shale with compacted clay.

The drainline encased in a gravel filter material was then placed inside the curtain and continued around the periphery of the plot. Upon leaving the plot area, the water is transported via solid pipeline to a measuring station where water quality and quantity is monitored.

The irrigation system is designed to deliver water through a closed conduit to each plot and allow measurement of the flows onto each plot. Since furrow irrigation is used almost exclusively throughout the valley, this method has been employed on the project area.

The crops being grown are corn, grass, alfalfa, and winter wheat, since these are the main crops grown commercially in the valley. By varying irrigation timing and amounts, crops, and nitrogen fertilizer levels on the different plots, and by monitoring quality and quantity of both inflow and outflow waters, the effects of these parameters on return flow salinity and crop yields can be evaluated.

One of the primary objectives of this research is to model the transport of salts in the soils in this area. The first portion of the flow of water and consequent transport of salts is through the root zone which is usually a zone of partial saturation. A numerical model of the moisture flow and chemical and biological reactions occurring in the root zone has been developed by Dutt et al. (1972). This is the basic model which will be used in this study to describe the salt transport being observed in the field.

The model consists of three separate programs. The first program describes the soil moisture movement and distribution with time. The second program interfaces the soil moisture movements with the chemical biological model. This is needed because the horizons used in the calculations of soil moisture and chemistry differ. The third program computes the chemical and biological activity occurring in the soil profile. Figure 6 is a block diagram of the overall model. A brief description of the moisture flow and chemical-biological models is included to serve as a basis for understanding the data collection requirements.

The flow is one dimensional and was developed using the Richards equation with a sink term. Schematically, the model is given in Fig. 7. Mathematically, the flow is described using Richards equation in the form:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left(\frac{D\partial\theta}{\partial x} - K\right) - S$$

where

θ = volumetric water content
t = time
x = length
K = hydraulic conductivity
S = sink term
D = diffusivity

This is the diffusivity form of the equation which means that only flow in the partially saturated zone of the soil profile can be described. The sink term (S) is computed using the Blaney-Criddle equations for evapotranspiration with the loss due to evapotranspiration being distributed through the soil profile by assuming a specific root distribution for the crop. The root distribution and coefficients for the Blaney-Criddle equations are supplied by the user.

Actual values of evapotranspiration can be used in the sink term when they are known. In this research, the necessary field data is being collected on-site that will utilize either Penman or Jensen-Haise evapotranspiration equations.

Salt transport is described by the following equation in one dimension.

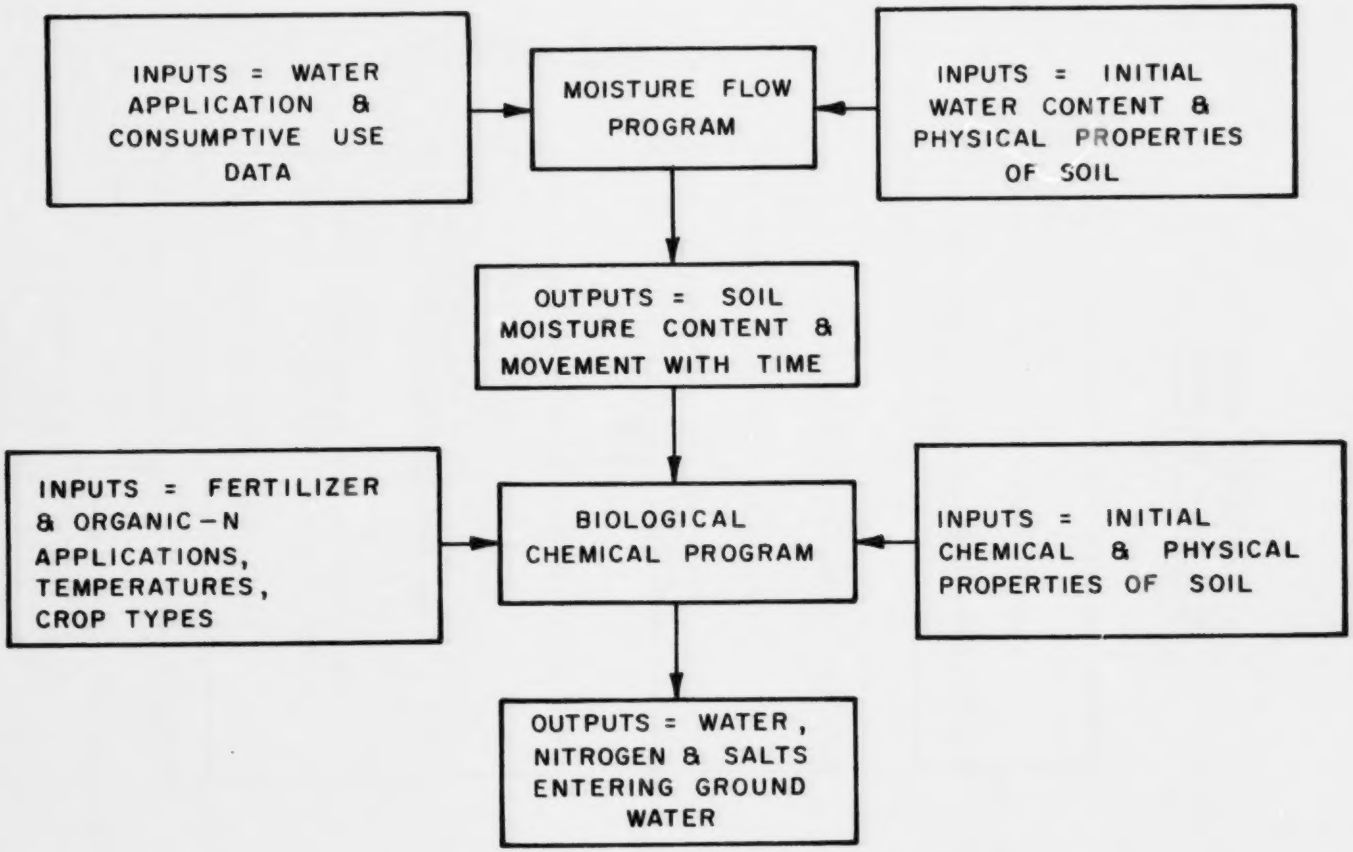
INPUTS = WATER APPLICATION & CONSUMPTIVE USE DATA
MOISTURE FLOW PROGRAM
INPUTS = INITIAL WATER CONTENT & PHYSICAL PROPERTIES OF SOIL
OUTPUTS = SOIL MOISTURE CONTENT & MOVEMENT WITH TIME
INPUTS = FERTILIZER & ORGANIC-N APPLICATIONS, TEMPERATURES, CROP TYPES
BIOLOGICAL CHEMICAL PROGRAM
INPUTS = INITIAL CHEMICAL & PHYSICAL PROPERTIES OF SOIL
OUTPUTS = WATER, NITROGEN & SALTS ENTERING GROUND WATER

Fig. 6. Generalized block diagram of the model. (Taken from Dutt, et al., 1972.)

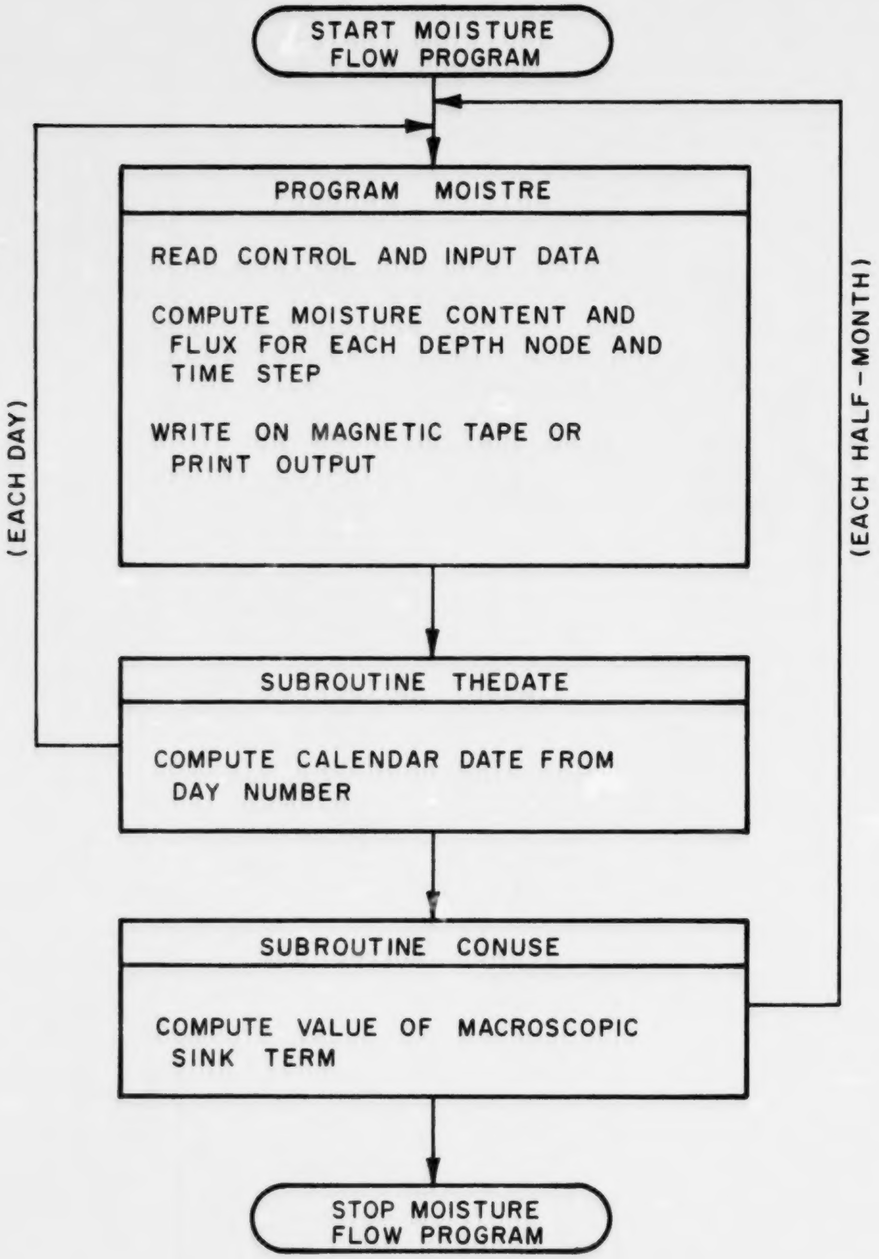
START MOISTURE FLOW PROGRAM
PROGRAM MOISTRE
READ CONTROL AND INPUT DATA
COMPUTE MOISTURE CONTENT AND FLUX FOR EACH DEPTH NODE AND TIME STEP
WRITE ON MAGNETIC TAPE OR PRINT OUTPUT
(EACH DAY)
(EACH HALF-MONTH)
SUBROUTINE THEDATE
COMPUTE CALENDAR DATE FROM DAY NUMBER
SUBROUTINE CONUSE
COMPUTE VALUE OF MACROSCOPIC SINK TERM
STOP MOISTURE FLOW PROGRAM

Fig. 7. Generalized block diagram of Moisture Flow Program. (Taken from Dutt, et al., 1972.)

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial c}{\partial z}\right) - \nu \frac{\partial c}{\partial z}$$

where

c = solute concentration
t = time
D = dispersion coefficient
z = depth
ν = flux or Darcy velocity

By assuming the term $\frac{\partial}{\partial z}(D \frac{\partial c}{\partial z})$ is negligible compared to $\nu \frac{\partial c}{\partial z}$ the equation reduced to $\frac{\partial c}{\partial t} = -\nu \frac{\partial c}{\partial z}$. This assumption implies that transport due to dispersion in partially saturated soils is negligible compared to the convective transport which occurs. This is generally a good assumption.

The model computes the moisture flow (ν) and couples the flow with the chemical changes $\frac{\partial c}{\partial z}$ computed in the biological-chemical program to give the salt transport. This technique is the basis for the mixing cell concept.

The chemical exchange model computes the equilibrium chemistry concentrations for calcium, magnesium, gypsum, sodium, bicarbonates, carbonates, chlorides, and sulfates. The nitrogen chemistry including ammonium, nitrates, and urea-nitrogen uses a kinetic instead of an equilibrium approach. The kinetic approach is needed since microbial activity involved in nitrogen transformation occurs over a period of weeks and days instead of minutes and seconds. The equilibrium chemistry for inorganic salts is a good approximation since the reactions describing their chemistry occur in a matter of minutes or seconds in a flow regime which is changing very slowly. A block diagram of the biological-chemical model is given in Fig. 8.

Preliminary studies have been made with this model to evaluate its capabilities and to insure compatibility with the available computer facilities. Analysis of last year's field data allowed extensive testing of the model. Modifications have been made to more accurately model existing field conditions.

Since the shale floor and plastic membrane walls act to create a box around each plot, the plot acts as a large lysimeter. A salt and water budget will be developed for each plot and compared to those developed for the other plots. From these data, equations can be developed to predict the variation in chemical quality (including ionic constituents) of the moisture movement through the soil profile, as well as the salt pickup resulting from movement of subsurface irrigation return flows over the Mancos shale beds. These results combined with the hydro-salinity

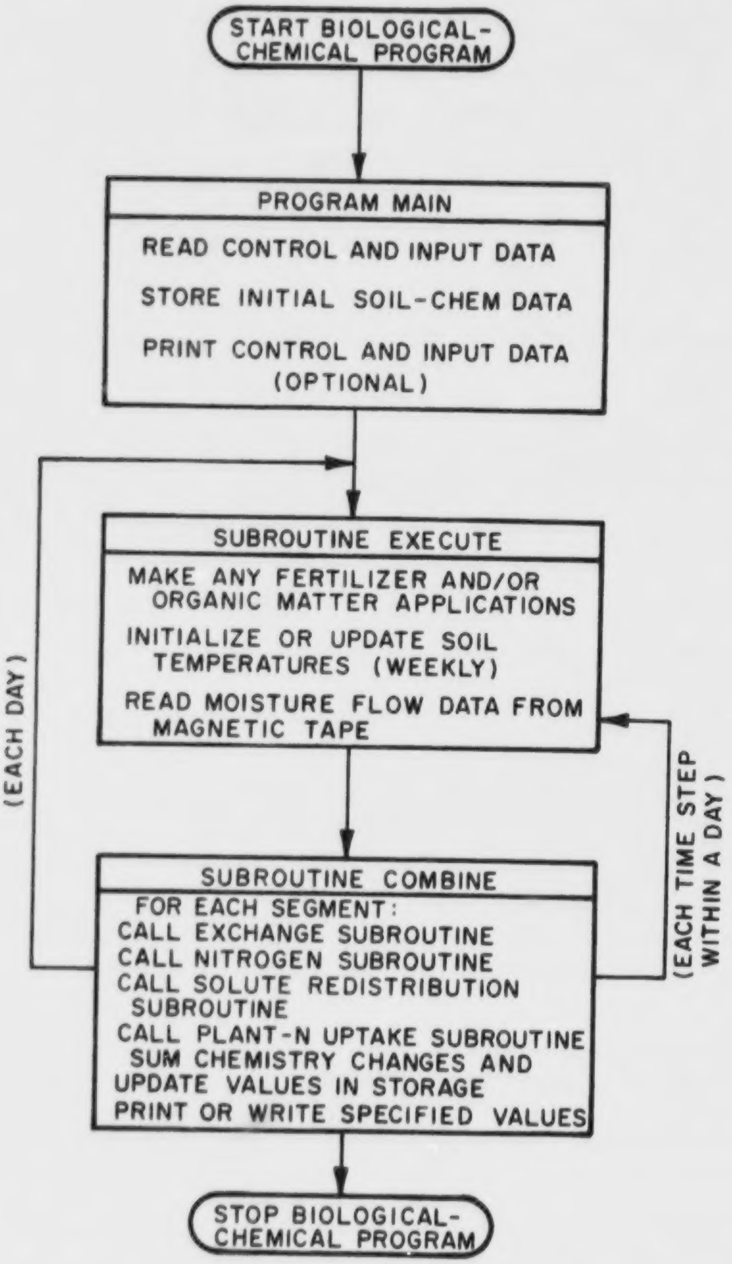
START BIOLOGICAL-CHEMICAL PROGRAM
PROGRAM MAIN
READ CONTROL AND INPUT DATA
STORE INITIAL SOIL-CHEM DATA
PRINT CONTROL AND INPUT DATA (OPTIONAL)
SUBROUTINE EXECUTE
MAKE ANY FERTILIZER AND/OR ORGANIC MATTER APPLICATIONS
INITIALIZE OR UPDATE SOIL TEMPERATURES (WEEKLY)
READ MOISTURE FLOW DATA FROM MAGNETIC TAPE
(EACH DAY)
(EACH TIME STEP WITHIN A DAY)
SUBROUTINE COMBINE
FOR EACH SEGMENT:
CALL EXCHANGE SUBROUTINE
CALL NITROGEN SUBROUTINE
CALL SOLUTE REDISTRIBUTION SUBROUTINE
CALL PLANT-N UPTAKE SUBROUTINE
SUM CHEMISTRY CHANGES AND UPDATE VALUES IN STORAGE
PRINT OR WRITE SPECIFIED VALUES
STOP BIOLOGICAL-CHEMICAL PROGRAM

Fig. 8. Generalized block diagram of Biological-Chemical Program. (Taken from Dutt, et al., 1972.)

model will allow an evaluation of various salinity control measures upon salinity reaching the Colorado River.

SALINITY CONTROL MEASURES

Channel Lining

The results of channel lining studies indicate that canal and lateral lining in the study area reduced salt inflows to the Colorado River by about 4,267 metric tons annually (Skogerboe and Walker, 1972). The bulk of this reduction is attributable to the canal linings, but clearly indicated is the greater importance of lateral linings. The length of laterals, including farm head ditches, is about ten times greater than the length of canals. The economic benefits to the Lower Basin water users alone exceed the costs ($350,000 construction plus $70,000 administration) of this project. Consequently, it seems justifiable to conclude that conveyance lining in areas such as the Grand Valley, where salt loadings reach 18 metric tons or more per hectare, are a feasible salinity control measure. The local benefits accrued from reduced maintenance, improved land value, and other factors add to the feasible nature of conveyance linings as a salinity management alternative.

The first and most important consideration in improving farm water use is control. Implied in this realization is the requirement of sound water measurement at the farm turnout and again at critical division points among farmers below the turnout. This would necessitate a considerable rehabilitation of both the canal and lateral system, and the implementation of a "call period" to allow canal operators more time for flexible water handling. In addition, it is an important requirement that the canal companies extend their control of the water below the canal turnout structure to include key division points within the lateral system to insure equitable allocation of water among users.

Irrigation Scheduling

The irrigation of agricultural lands in the Colorado River Basin is a significant cause of the salinity concentrations encountered in the Colorado River. Emphasis towards stemming further salinity increases has logically centered upon improving the quality of irrigation return flows. This emphasis, especially in the high salt contributing areas like the Grand Valley in western Colorado, focuses upon reducing the flows which pass through the saline soils and aquifers, thereby reducing the salt pickup that occurs by dissolution. Since a major fraction of the water contacting local soils in this manner comes from over-irrigation, measures aimed at improving irrigation efficiencies promise good potential for controlling salinity. Among the methods for achieving higher water use efficiencies on the farm, "scientific" irrigation scheduling is possibly the most important (Skogerboe et al., 1974).

Irrigation scheduling consists of two primary components; namely, evapotranspiration and available root zone soil moisture. Evapotranspiration is calculated by using climatic data. The other major category of required data pertains to soil characteristics. First of all, field capacity and wilting point for the particular soils in any field must be determined. More importantly, infiltration characteristics of the soils must be measured. Only by knowing how soil intake rates change with time during a single irrigation, as well as throughout the irrigation season, can meaningful predictions be made as to: (a) the quantity of water that should be delivered at the farm inlet for each irrigation; and (b) the effect of modifying deep percolation losses. With good climatic data and meaningful soils data, accurate predictions as to the next irrigation date and the quantity of irrigation water to be applied can be made. In order to insure that the proper quantity of water is applied, a flow measurement structure is absolutely required at the farm inlet.

The results of this demonstration project indicate that irrigation scheduling programs have a limited effectiveness for controlling salinity in the Grand Valley under existing conditions. Excessive water supplies, the necessity for rehabilitating the irrigation system (particularly the laterals), and local resistance to change preclude managing the amounts of water applied during successive irrigations. To overcome these limitations, irrigation scheduling must be accompanied by flow measurement at all the major division points, farm inlets, and field tailwater exits. In addition, it is necessary for canal companies and irrigation districts to assume an expanded role in delivery of the water. Also, some problems have been encountered involving poor communication between farmer and scheduler, as well as certain deficiencies in the scheduling program dealing with evapotranspiration and soil moisture predictions. These latter problems can be easily rectified, however. Correcting these conditions will make irrigation scheduling much more effective and acceptable locally.

Water budgets from which the study results were generated resulted from intensive investigation on two local farms. The selection of the two study farms was intended to be representative of conditions valley-wide. Analysis of the budgets reveal that approximately 50% of the water applied to the fields came during the April and May period when less than 20% of the field evapotranspiration potential had been experienced. Salt pickup estimates during this early part of the season amounted to about 60% of the annual total for each field. Another indication of the importance of early season water management is presented in an analysis of irrigation efficiencies. As the season progressed, the soils became less permeable and the crop water use increased, causing marked improvements in irrigation efficiency. Thus, if irrigation scheduling is employed in its optimal format, salt pickup from the two fields could have been reduced as much as 50% or more.

The results of this demonstration project show that irrigation scheduling is a necessary, but not sufficient, tool for achieving improved irrigation efficiencies. The real strides in reducing the salt pickup resulting from over-irrigation will come from the employment of scientific irrigation scheduling in conjunction with improved on-farm irrigation practices. This combined effect could result in a reduction of 270,000 metric tons annually of salt pickup from the Grand Valley, depending upon the degree of improvement in present on-farm irrigation practices.

Drainage

Drainage investigation in the Grand Valley began shortly after the turn of this century when local orchards began failing due to high saline water tables. Study showed the soils to be not only saline but also having low permeabilities. At the time, the future development of the Bureau of Reclamation's "Grand Valley Project" loomed as a severe threat to the low lying lands between it and the Colorado River. In answer to these drainage needs, the solutions were clearly set forth but never fully implemented. Rather, a local drainage district was formed to construct open ditch drains and some buried tile to correct trouble spots. All of these efforts barely stopped the rise in water table, and today more than fifty years later, the local conditions remain essentially unchanged.

This study was undertaken with the history of local drainage well in mind, but for a different purpose - that being the skimming of water from the top of the water table before it reaches equilibrium with the highly saline soils and aquifers. A farm owned by Mr. Wareham was used in the study to demonstrate the skimming effect by installing field relief drains on 12.2 meter centers. The field had been under poor irrigation management for several years, so the results are not immediately discernable. However, analysis of water quality throughout the study area indicated that relief drainage, if effective, would interrupt flows with a salinity concentration as much as 3000 meq/l lower than existing groundwater concentrations.

In viewing the results of this study, it is obvious that field drainage is a curative rather than preventative measure. High costs of such programs illustrate the need of first minimizing the flows passing through the root zone or seeping from canals and laterals. The small amount of water entering the groundwater could then be effectively removed by drainage systems located at selected locations. Thus, field drainage as it pertains to objectives of salinity control is a remedy which must be considered but will probably not be orderly implemented until the later stages of salinity control in the valley (Skogerboe et al., 1974).

As part of the study, an alternative use of drainage was considered. This involved the collection of and desalting of drainage effluents. During the 1940's, pump drainage from a deep cobble aquifer was tested and proved most effective. In determining the costs of pump drainage and desalting as well, it became apparent that these alternatives are also too costly to be feasible in the immediate future. However, with the recent advances in desalination technology, this alternative method of removing salts from irrigation return flows is certain to become increasingly feasible as time progresses.

DEMONSTRATION OF SALINITY CONTROL MEASURES

The principal study area in Grand Valley, which has been used for evaluating the effectiveness of canal and lateral lining, as well as irrigation scheduling and tile drainage, in reducing the salt load entering the Colorado River is now being used as a demonstration project, beginning in February, 1974. The advantage in continuing to utilize this study area is that the hydrology is already known. In addition, there has been considerable expenditure of funds in both equipment and personnel for instrumenting this particular demonstration area. The wealth of available information provides a strong basis for evaluating the effectiveness of salinity control measures.

With the available knowledge regarding the study area, a lateral including the associated land served by the lateral water supply can be used as a sub-system for evaluating the salinity reduction in the Colorado River resulting from the implementation of a salinity control technology package. The study area was originally selected because of being fairly representative of the Grand Valley, while having five canals traverse the area, thereby allowing greater participation by the majority of irrigation entities in the valley.

The project was initiated by a newspaper article inviting interested parties to an explanatory open-house. More farmers responded to the open-house than could be included in the study. A strong emphasis was made at the open-house discussions that our primary interest in undertaking this research demonstration project was to reduce the salt load in the Colorado River; however, a significant by-product of this emphasis would be increased agricultural productivity under the lateral sub-systems improved by this effort. Meetings were later held in the homes of the interested irrigators under the several lateral sub-systems and specific details for cost-sharing and anticipated types of irrigation system improvements were discussed, including the time schedule for pre-construction field investigations, construction, and post-construction operations.

In order to facilitate continued participation by most irrigation interests in Grand Valley, this demonstration project has utilized laterals under each of the five canals in the study area. These particular laterals have been selected to represent a wide variety of conditions. A few of the laterals have already been extensively lined with concrete under the previous demonstration project.

The irrigated lands served by the selected laterals represent a wide variety of irrigation and drainage problems. However, most of the emphasis was placed upon improvements in the southern half of the demonstration area which have the most serious waterlogging and salinity problems of any lands in the valley. Making improvements on the poorest lands has a definite advantage, provided the program is successful in increasing crop production and in gaining farmer acceptance and credibility. Also, this approach overcomes farmers' criticisms regarding field experiment stations that ... "the best lands are used, and they have lots of money and people, so they should be able to grow better crops."

Frequent meetings were held with the water users under each lateral to discuss alternative plans for improving water delivery. Potential on-farm irrigation improvements were discussed individually with each water user. These meetings provided the means for developing a concensus for collective action.

The laterals have been selected to capitalize on previous work regarding canal and lateral lining, as well as irrigation scheduling and drainage studies. The hydrologic knowledge already gained in this demonstration area allows routine surface water and groundwater monitoring to evaluate the overall effectiveness of the salinity control technology package. Fortunately, the portion of lands that have undergone treatment under this demonstration project along with previously constructed channel lining and drainage facilities, will provide a significant impact upon salinity leaving the demonstration area.

The experimental design for the pre-evaluation was primarily aimed at providing specific information for the 330 hectares undergoing treatment. The field data collection program provided necessary data for the design of irrigation and drainage facilities, as well as providing sufficient data to allow predictions of salinity benefits that should result from each specific salinity control measure. Although the post-evaluation includes the monitoring of water and salts entering and leaving the demonstration area, the primary emphasis is the on-site evaluation of each specific salinity control measure. The on-site evaluation can then be compared with the results of the demonstration area monitoring program, which in turn can be expanded to a valley-wide evaluation. The laterals being utilized in this program are shown in Fig. 9, while Table 5 lists the improvements that have been constructed.

The selection of a lateral as a sub-system, rather than an individual farm, has a tremendous advantage in allowing control at the lateral turnout. In this way, both the quantity of flow and the time of water delivery can be controlled, thereby facilitating improved water management throughout the sub-system.

The construction program was initiated in the fall of 1974, with the bulk of the construction being completed in the spring of 1975. However, some of the construction had to be completed after the 1975 irrigation season. Most of the 1975 irrigation season was devoted to working the "kinks" out of the various improvements in order to make the systems operate effectively. During the 1976 irrigation season,

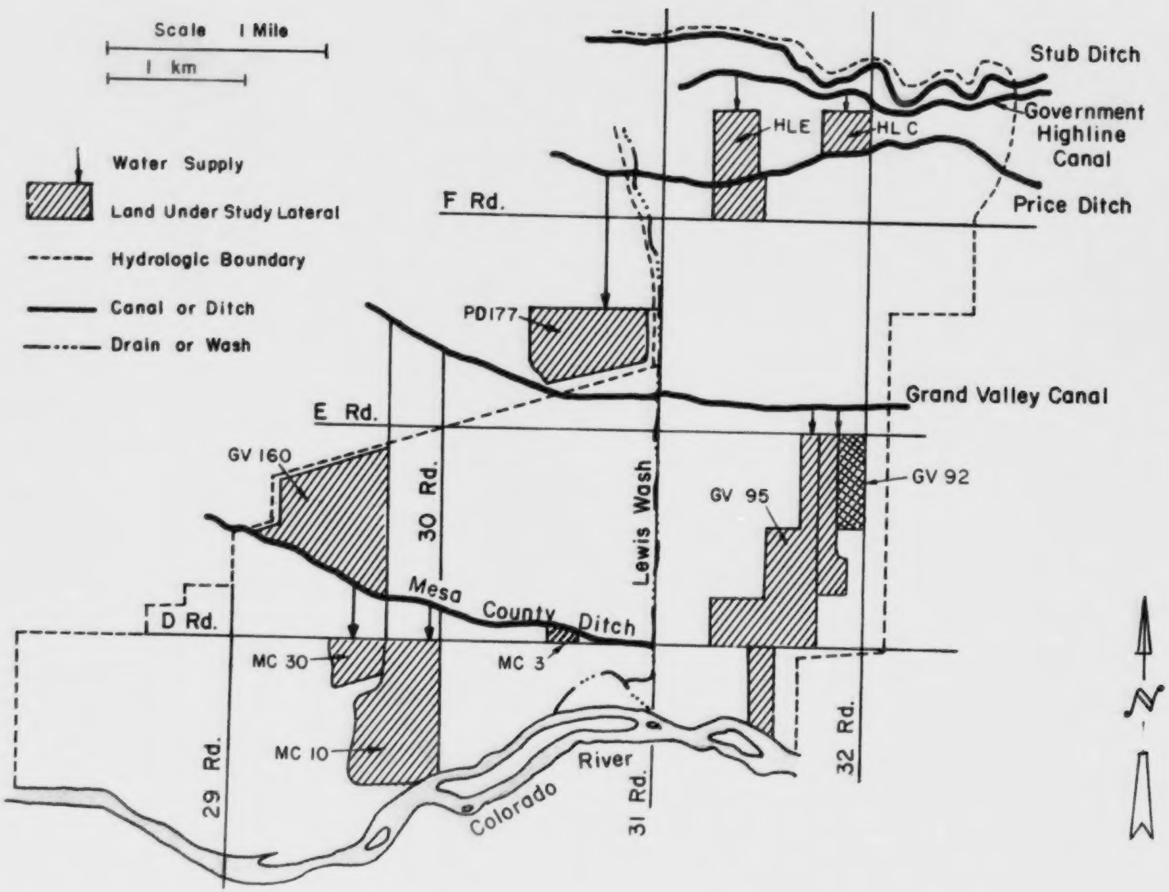
Scale 1 Mile
1 km
Water Supply
Land Under Study Lateral
Hydrologic Boundary
Canal or Ditch
Drain or Wash
Stub Ditch
Government Highline Canal
Price Ditch
HLE
HL C
F Rd.
PD177
Grand Valley Canal
E Rd.
GV 160
30 Rd.
Lewis Wash
GV 95
GV 92
Mesa County Ditch
D Rd.
MC 30
MC 3
MC 10
River
Colorado
29 Rd.
31 Rd.
32 Rd.
N

Figure 9. Location of the nine selected lateral systems incorporated in the project.

Table 5. Completed Improvements by laterals for Grand Valley Salinity Control Demonstration Project.

TYPES OF IMPROVEMENTS	LATERAL									
	HL C (13.1 ha)	HL E (35.9 ha)	PD 177 (27.8 ha)	GV 92 (24.2 ha)	GV 95 (79.2 ha)	GV 160 (78.6 ha)	MC 3 (3.6 ha)	MC 10 (54.0 ha)	MC 30 (14.0 ha)	TOTAL (330 ha)
Concrete Ditches (m)		1/	230 1/	190	2789	1899	157	2723 1/	1040	9,028
Buried Plastic Pipelines										
Gravity systems (m)		390.1	2066.5	816.9	2364.0	2548.1		1054.6	195.1	9,432.3
Pressurized systems (m)		134.1			378					512.1 4/
Gated Pipe (m)			207.3		615.7			600.5	121.9	1,545.4
Drip Irrigation (ha)			2.2							2.2
Overhead Sprinklers (ha)		5.2								5.2
Sideroll Sprinklers (ha)					4.0					4.0
Drainage Works (ha)	2.2				6.5	11.5	2.5	6.1	2/	28.8
Plastic Drainage Tile (m)					2667.0	3496.1	1958.3	4957.6		13,079
Concrete Drainage Tile (m)	244									244
Flow Measurement (No.)	(3)	(5)	(18)	(3)	(25)	(27)	(3)	(18)	(5)	(105 TOTAL)
Cutthroat Flumes (No.)		2	3	2	18	26	2	14	3	70
90° V-Notch Weirs (No.)	1		1		1					3
Parshall Flumes 3/ (No.)	2		3		1			2	2	10
12" Propellor Meters (No.)			1		1			1		3
10" Propellor Meters (No.)			1		2					3
8" Propellor Meters (No.)		1	3		1	1		1		7
Other Meters (No.)		1			1					6
Metering Headgates (No.)				1			1			2
Debris Removal Equipment (No.)		1	1		1					3
Land Shaping, etc. (ha)					24.3			11.3		35.6
Irrigated area (Possible) (ha)	10.9	24.9	21.1	18.8	69.6	61.3	3.0	42.7	13.8	266.1
Total Value	$4879.82	$20421.49	$36140.28	$15287.88	$98057.65	$83628.42	$17444.80	$66940.42	$8534.23	$351,335.01
Cost/Irr. ha	$ 447.69	$ 820.14	$ 1712.81	$ 813.19	$ 1408.70	$ 1363.97	$ 5904.87	$ 1569.34	$ 620.24	

1/ These laterals were part of the earlier lateral lining study and already contained a combined total of approximately 122 m of concrete ditch.

2/ This lateral was part of a previous drainage study and already contained approximately 3,353 m of plastic drainage tile on 4 ha.

3/ These flumes will be removed at the end of the project since they measure field runoff.

4/ The pressurized pipelines are included in the sprinkler systems for cost purposes.

the nine laterals are being operated as sub-systems, wherein irrigation scheduling is being used as the guide to operating most of the laterals. At the same time, additional field data is being collected to provide information for advising farmers regarding improvements and refinements in irrigation practices.

A variety of irrigation methods are being demonstrated, including improving present irrigation methods being used in the study area. Considerable experience has been gained in improving the existing irrigation methods while evaluating irrigation scheduling as a salinity control measure in Grand Valley. However, more advanced irrigation methods are just now being evaluated as to salinity benefits in Grand Valley. The irrigation systems that have been constructed under this project include automated farm head ditches, border irrigation, sprinkler irrigation, and trickle irrigation. Thus, one of the significant results from this project will be the preparation of a report, "Evaluation of Irrigation Methods for Salinity Control in Grand Valley."

The most significant aspect of this particular demonstration project is the employment of a salinity control technology "package," rather than a single control measure. Experience in Grand Valley has shown that most significant progress is made when the gamut of questions can be answered regarding the interrelationships between water management and agricultural production. Thus, the concept of a technology package, along with an understanding of the "system" including other agricultural inputs, provides the necessary base for providing sound advice to the farmer, which in turn facilitates the development of credibility and consequently farmer acceptance.

A two-day "Irrigation Field Days" was conducted during August 6-7, 1976. This event was primarily directed towards the farmers in Grand Valley and secondly to irrigation leaders (mostly farmers) throughout the Upper Colorado River Basin. Many State and Federal agency personnel throughout the West also attended.

FINAL RESEARCH EVALUATION

The currently funded EPA research project, "Irrigation Practices, Return Flow Salinity, and Crop Yields," which is nearing completion in Grand Valley, will be utilized in developing the cost-effectiveness of each salinity control measure. In addition, the results from the research project will provide valuable information regarding increased crop yields that can be expected from improved water management practices. The combined results of the research project and the demonstration project are extremely important in establishing the benefits to be derived from implementing a salinity control technology package.

The results from the demonstration project will be projected to valley-wide conditions in preparing the report, "Best Management Practices for Salinity Control in Grand Valley." This report, which will integrate eight years of concentrated study in the valley, will serve as a basis for an action salinity control program. Such a program would detail the optimal strategy for implementing various levels of individual salinity control measures into a comprehensive technology package. To develop this kind of policy, cost-effectiveness functions relating the reductions in the system salt loadings resulting from a specified investment would be individually assessed in an optimizational format to arrive at the least cost combination for achieving a desired level of salinity control. The analytical procedures which are being used to determine the optimal combinations of salinity control technologies is described in another paper of these proceedings (Walker, 1976). Since salinity control in Grand Valley must evolve with the development of water resources in the Upper Colorado River Basin, this report will describe the time-varying characteristics of salinity control strategies. As other critical regions require salinity management, this report would serve as a procedural document illustrating analytical methodologies, data requirements, and strategy structures.

IMPLEMENTATION

A full-scale salinity control program is expected to get underway in Grand Valley during late 1977. The action agencies will be the U.S. Bureau of Reclamation and the Soil Conservation Service. At this time, a combined program of canal and lateral lining, on-farm irrigation improvements, and drainage is expected which will likely cost more than $100 million.

ACKNOWLEDGEMENTS

The work reported herein has been supported by the U.S. Environmental Protection Agency, Office of Research and Development. The cooperative efforts by the Project Officer, Dr. James P. Law, Jr., Chief of the Irrigated Agriculture Section, Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma is sincerely appreciated.

REFERENCES

Dutt, G. R., M. J. Shaffer, and W. J. Moore. 1972. Computer simulation model of dynamic bio-physiocochemical processes in soils. Technical Bulletin 196, Department of Soils, Water and Engineering, Agricultural Experiment Station, University of Arizona, Tucson. October.

Hyatt, M. Leon. 1970. Analog computer model of the hydrologic and salinity flow of systems within the Upper Colorado River Basin. Ph.D. dissertation, Department of Civil Engineering, College of Engineering, Utah State University, Logan, Utah. July.

Iorns, W. V., C. H. Hembree, and G. L. Oakland. 1965. Water resources of the Upper Colorado River Basin - Technical Report. Geological Survey Professional Paper 441. U.S. Government Printing Office, Washington, 369 p.

Luthin, L. N. 1966. Drainage Engineering, John Wiley and Sons, Inc. New York. 250p.

Skogerboe, G. V. and W. R. Walker. 1972a. Evaluation of canal lining for salinity control in Grand Valley. Environmental Protection Technology Series, EPA-R2-72-047. Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington, D.C. October.

Skogerboe, G. V., W. R. Walker, J. H. Taylor, and R. S. Bennett. 1974. Evaluation of irrigation scheduling for salinity control in Grand Valley. Environmental Protection Technology Series, EPA-660/2-74-052. Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington, D.C. June.

Skogerboe, G. V., W. R. Walker, R. S. Bennett, J. E. Ayars, and J. H. Taylor. 1974. Evaluation of drainage for salinity control in Grand Valley. Environmental Protection Technology Series, EPA-660/2-74-084. Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C. August.

U.S. Environmental Protection Agency. 1972. Proceedings: Conference in the matter of pollution of the interstate waters of the Colorado River and its tributaries - Colorado, New Mexico, Arizona, California, Nevada, Wyoming, and Utah. Regions VIII and IX, Denver, Colorado. April.

U.S. Environmental Protection Agency. 1971. The mineral quality problem in the Colorado River Basin. Summary Report and Appendices A, B, C, and D.

Walker, W. R. 1970. Hydro-salinity model of the Grand Valley. M.S. Thesis CET-71WRW8. Civil Engineering Department, College of Engineering, Colorado State University, Fort Collins, Colorado. August.

Walker, W. R. 1976. Integrating desalination and agricultural salinity control technologies. Paper presented at the International Conference on Managing Saline Water for Irrigation, Texas Tech University, Lubbock, Texas. August 16-20.

Walker, W. R. and G. V. Skogerboe. 1971. Agricultural land use in the Grand Valley. Agricultural Engineering Department, Colorado State University, Fort Collins, Colorado. July.

Westesen, G. L. 1974. Salinity Control for Western Colorado. Unpublished Ph.D. Dissertation. Agricultural Engineering Department, Colorado State University, Fort Collins, Colorado.

ON-FARM WATER MANAGEMENT PRACTICES FOR ALLEVIATING WATERLOGGING AND SALINITY PROBLEMS IN PAKISTAN

Gaylord V. Skogerboe[1]

INTRODUCTION

The irrigation system of Pakistan represents one of the largest modern conveyance systems in the world. The hydraulic features of dams, barrages, canals, distributaries, structures, and appurtenances have been fully described in other publications. There is however a paucity of information and, indeed, a lack of understanding of that portion of the irrigation system with which the farmer deals. This refers to the system from the canal outlet (mogha) through the irrigated field. The farmer operates and manages this water with little or no governmental assistance. The procedures, rules, resources, and constraints at his disposal determine his on-farm water management practices, which determine the crop production per unit of irrigation water. A description of this farmer operated system, the rationale for its present conditions, an evaluation of the problems, and suggestions for improvement are presented herein with the hope that increased production through improved water management will result. The potential for increasing production through water management is great (Corey and Clyma, 1973).

DESCRIPTION OF IRRIGATION SYSTEM

The climate and soils of Pakistan are especially suitable for agriculture; however, precipitation is totally inadequate in some areas and insufficient in others for more than modest production. Without supplemental water this area would revert to deserts with only sparse vegetation. Irrigation is the key to a productive agriculture in Pakistan.

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A modern irrigation conveyance system was constructed in Pakistan by the British in the late 1800's and it is one of the largest in the world. There are about 60,000 kilometers of canals which command a gross area of 13 million hectares of fertile soils. About 10 million hectares actually receive surface water. Today there are more than 100,000 tubewells supplementing the Indus system with 2.5 million hectare-meters (ha-m) annually. Over 200,000 persian wheels also provide supplemental water. There are about 13 million hectares of deep alluvial soils under irrigation in the Indus basin containing three million individual farms with a median size of 2.1 hectares. This probably constitutes the greatest single agricultural potential in the world.

The system is not only large with a vast potential, but it is unique in several other aspects. One disappointing feature, however, is the present low production in light of the apparent highly suitable soil, water, and climatic resources. These factors suggest a production potential many times greater than presently achieved. The "green" revolution increased production appreciably, but even this appears to be far below potential.

Many experts agree that the farming practices, including irrigation water management, must be modernized in order to achieve higher production. The White House-Department of Interior Panel on Waterlogging and Salinity in West Pakistan (Revelle et. al., 1964) noted: "In West Pakistan we have the wasteful paradox of a great and modern irrigation system pouring its water on lands cultivated as they were in the middle ages..." This observation is quite obvious to anyone acquainted with irrigated agriculture in Pakistan, but the causative conditions and factors are neither obvious nor simple. It is ironic that the only Revelle (1964) recommendation meeting with any degree of success was the one which enhanced the "great and modern irrigation (conveyance) system". The modern system ends at the mogha.

Water Delivery

Pakistan has over 80,000 watercourses with an average culturable command area of 160 hectares each. This means the average watercourse serves 40 farmers and that a normal village of 100-120 farms will have approximately three watercourses. Since watercourse command areas are topographically determined and land ownership is not, it can happen that one watercourse serves lands owned by farmers in different villages. Conceivably, either the watercouse or the village could serve as the basic organizational unit for a water management program. There appears to be several sociological reasons suggesting the village as the organizational unit.

The irrigation system is so constructed that water flows from the minor canals through turnouts (moghas) supplying water to a village area. The farmers themselves operate and maintain their distribution system. There are no headgates at the moghas and if a particular canal has water in it, there is water in every watercourse (khal) on that canal. It is like a giant river system flowing in reverse with each tributary getting an equal share. The farmers on the watercourse use the entire flow on a turn based on his acreage and he has a fixed time each week, 10 days, or two weeks to use it. If there is insufficient water during a particular farmer's turn, then he must forfeit his share of public canal water and wait for the next turn. There are some variations which are unofficial but water on demand is essentially unknown except in those areas served by farmer operated tubewells (Corey and Clyma, 1973).

The watercourse system does not always flow full, depending on supplies in the canals; therefore water available on the "warabundi" is not always constant. Canal closures for repairs do occur and farmers are not usually notified in sufficient time to make alternate plans. Water charges are made on the basis of acreage of crop grown and water rates vary for different crops based on assumed consumptive rates. Mixed crops are assessed at the highest rates leviable on any one crop. If a portion of a field is irrigated, the rate applies for the whole field unless such portion has been clearly demarcated by a well defined ridge. The assessment for irrigation water therefore is not based on the amount of irrigation water received, but on the acreage and species of crops grown in a partiular season. The individual (potwari) who makes the levy for each crop is greatly underpaid and as a result of the vast amounts of water rates he levies, he often finds it lucrative to reduce rates for special favors from farmers (Corey and Clyma, 1973).

The topography of the Indus basin is flat. The general slope downstream averages less than 0.2 meters per kilometer. Natural drainageways are not readily apparent since most of the area has low rainfall and runoff in the irrigated area is minimal. Practically no artificial drains have been constructed, therefore surface drainage for irrigation water is virtually nonexistent either from artifical or natural drains. Irrigation water passing through each "mogha" is therefore utilized on that particular watercourse area as there is no provision to let it pass to an area of lower elevation.

The soils are characterized as having a special granulometrid distribution. The ratio of silt to clay is high with some resemblance to loess soils. There is a lack of structure which is perhaps related to the quantity of organic matter in the soil. This lack of organic matter, improper tillage methods, and a problem of cementation of the homogeneous soil particles result in low infiltration rates for most of the silty and sandy loam soils.

The irrigation system and resources provide the farmer with special problems not fully understood by the casual observer to agriculture in Pakistan.

Irrigation Method

The inundation or level basin system of irrigation is used extensively in Pakistan. The flat topography might suggest this practice but actually the constraints are such that no other system is possible. The non-runoff restriction requires either a system in which water is applied precisely according to the infiltration rate or it must be ponded. The low infiltration capacities of most soils make it impossible to get sufficient water into the profile during one irrigation turn. The level basin system has been utilized because it exactly fits these resources and constraints. Furrow irrigation is practiced with some crops and it is interesting to observe that the furrows are constructed to provide for a great deal of storage. The ponding method, then, is also used with this system; the furrows are made very broad and will store sufficient water to fill the soil reservoir even though infiltration rates require that the opportunity time be much longer than the "warabundi" turn. Apparently, the furrow system is only used with those crops such as tobacco, sugar cane, and vegetables which will not tolerate inundation for extended periods. Regardless of whether basins or furrows are used a ponding procedure requires a level system. Water must be stored on the surface during irrigation and allowed to stand and infiltrate into the plant root zone (Corey and Clyma, 1973).

The farmer has attempted to farm his land on a dead level basis with traditional implements drawn by bullocks. He appreciates the very small tolerance in elevation difference required with such field design. A one inch (2.5 cm) difference in elevation frequently means more than a two inch (5 cm) difference in water stored in the root zone and this can be as much as fifty percent of the water needed for proper plant growth. His traditional tools for accomplishing land leveling have been less than ideal. Bullock drawn logs and boards (sohaga and karah) are commonly used. Tractor blades and bulldozers are now available to those with sufficient capital; however, none of these tools are appropriate for preparing fields precisely to a dead level tolerance. Precision land leveling can only be accomplished effiiently by utilizing known engineering principles and procedures for design together with proper machinery expertly handled. Machines which load and carry an appreciable amount of soil while scraping over a surface thin layer have proved ideal for this job. These machines act as planes and perform the very important job of compacting loose soil as well as cutting to a precise depth. Such machines which are usually called soil scrapers and land levelers are now manufactured in Pakistan and are increasningly available to the farmers.

Without this equipment or the technical skills required to design and construct a dead level field, the farmer has developed his own crude leveling procedure. He utilizes the water itself to provide a measure of levelness and by continually re-leveling with the "sohaga" and the "karah" he maintains a reasonably workable field. Of necessity he has had to develop a system of very small fields because he cannot maintain a small tolerance over a large land area. Ordinarily he selects a parcel only about one acre in size as a unit for water control. He further divides this into four and frequently eight equal parts with dikes (bunds). It is common to observe a series of one acre benches each representing a separate irrigation unit.

A system utilizing small fields naturally results in an extensive water conveyance system. These open ditches supply water to practically every acre and it is difficult to find a point within an irrigated area which is more than three hundred feet away from a water supply ditch. The length of the watercourse per acre is very large due to the constraints of the traditional irrigation system. There is little alternative to such a system without external services and assistance to the farmer.

WATERLOGGING AND SALINITY IN PAKISTAN

Problem Development

The Indus Plain is an arid to semi-arid region containing alluvial soils. In this type of climate, the salts were deposited in varying degrees when the alluvium was laid down. At the turn of the century, prior to the major conversion of inundation canals to weir-controlled canals, the water table in the center of the doabs and in other portions of the Indus Plains was eighty feet or more below the surface (Khan, 1974). Doab is a term meaning the land area lying between two rivers which join at the lower end of the doab. There are four doabs (Figure 1) in the Punjab, namely, the Thal Doab, Chaj Doab, Rechna Doab, and Bari Doab.

Due to the flat topography in the Indus Basin and the large increase in irrigated area during this century resulting from the construction of perennial canals, the water table gradually rose over a large area. The water table is now near the ground surface in many

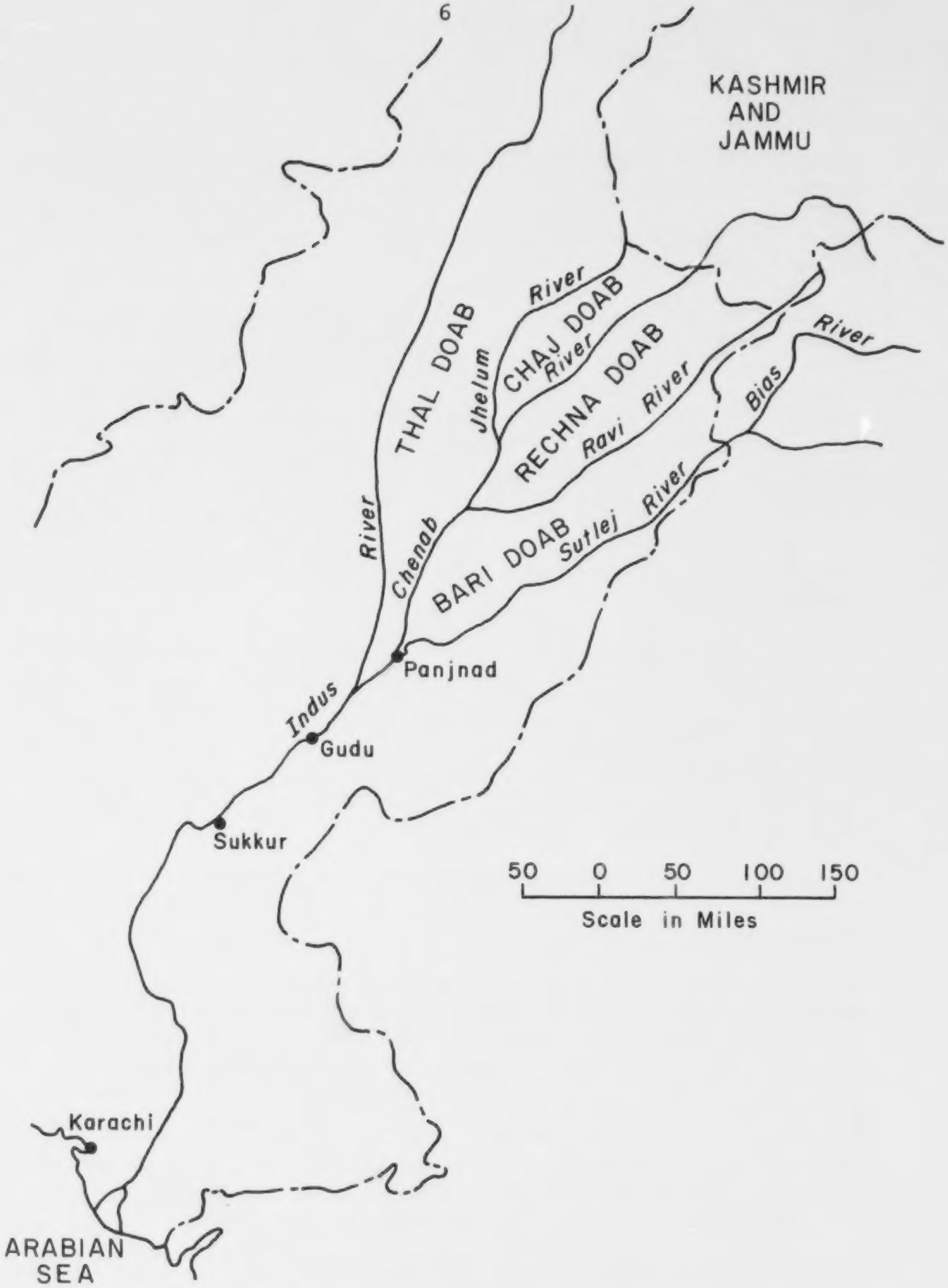

6
KASHMIR AND JAMMU
THAL DOAB
CHAJ DOAB
RECHNA DOAB
BARI DOAB
Jhelum River
Chenab River
Ravi River
Sutlej River
Bias River
Indus River
Panjnad
Gudu
Sukkur
Karachi
ARABIAN SEA
50 0 50 100 150
Scale in Miles

Figure 1. Location map of doabs in the Punjab.

areas, which results in waterlogging. Because of the high water table and lack of drainage, hundreds of thousands of hectares of land have become saline. Tens of thousands of hectares are going out of cultivation each year due to waterlogging and increased salinity. The average rise of the groundwater table has been between 10 to 50 cm per year (Mohammed and Beringer, 1963).

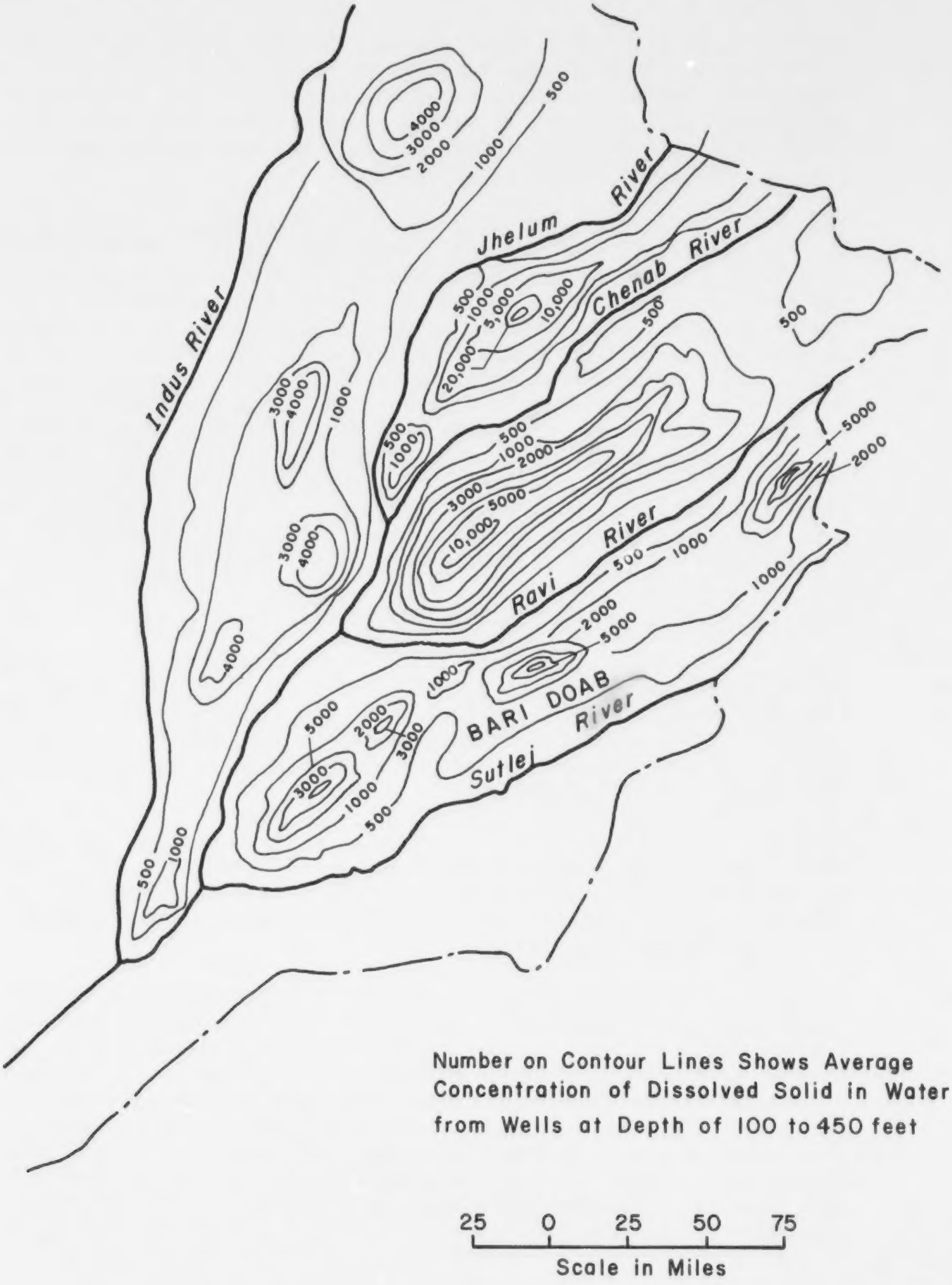
When the water table approached to within three meters of the ground surface, capillary rise and soil evaporation began. The salts left behind by evaporation were deposited on the fields and within a few years the soil salinity increased to a level that retarded and ultimately prevented crop growth. Since most crops have only a limited salt tolerance, the land becomes useless. The process by which agricultural lands become unfit for agricultural production through waterlogging and salinity is a gradual one. According to the Revelle (1964) Report, the total area severely affected by salinity was two million hectares, or about 18 percent of the gross sown area. Much of the salt affected areas are located in the central area of the doabs where the water tables are high. Also, the salinity concentrations are greatest in the center of the doabs as shown in Figure 2 (Greenman, Swarzenski, and Bennett, 1967).

Efforts to Control Waterlogging and Salinity

Attention towards waterlogging first occurred in 1851, when malaria became a serious problem in Western Jamina Canal (now in India). Systematic observation on water levels were initiated in 1870. First of all, monsoon rainfall was considered the main reason for high water tables. Then, storm-water drains for rapid removal of monsoon rainfall runoff were constructed.

Many attempts have been made in the past to reclaim salty and waterlogged lands. Among the various measures tried were lining of selected reaches of canals, lowering of the levels of the canals, closures of the canals in the winter, and construction of drains in severely affected localities.

The problem of waterlogging and salinity was first noticed in the upper region of Rechna Doab a few years after the opening of Lower Chenab Canal in 1892. At that time salinity was attributed to the high water table conditions, with groundwater as the source of salt. Investigations in deep water table areas, carried out later in 1937, brought to light that salts were originally present in the soil and that their movement towards the surface was caused not only by the rising water tables but also by inadequate irrigation applications, and improper irrigation practices. As a result of these findings the salinity and alkalinity survey work was extended in 1943 to the


Indus River
Jhelum River
Chenab River
Ravi River
Sutlej River
BARI DOAB
500
1000
2000
3000
4000
5000
5,000
10,000
20,000
25 0 25 50 75
Scale in Miles

Number on Contour Lines Shows Average Concentration of Dissolved Solid in Water from Wells at Depth of 100 to 450 feet

Figure 2. Salinity of Shallow Groundwater in the Punjab.

entire irrigated areas of Punjab Province and by 1960 to other regions of Pakistan (Irrigation, Drainage and Flood Control Research Council, 1975).

Open field drains and collector drains were found to be more beneficial and economical than other types of drains. In 1918, eighty miles of drains were dug. When Pakistan came into existence, there were about 2300 miles (3700 km) of drains constructed in the Rechna and Chaj doabs. For quite some time, engineers and soil scientists in the Punjab have recognized the seriousness of the gradual waterlogging of lands within the various doabs of the province and the deterioration of lands because of salinity (Mohammad, 1965).

In 1952, the Government of Pakistan requested the Government of Canada, through the Columbo Plan Administration, to arrange an air photography and resources survey in Pakistan. The work was accomplished by the Photographic Survey Corporation, Limited of Toronto, Canada. A total area of 110,961 square miles was photographed, which lies largely within the Indus Plains. The result of this survey was reported in a document published in February, 1958, entitled "Land Forms, Soils and Land Use of Indus Plains - West Pakistan." This survey indicated that of the 71 million acres (29 million hectares) surveyed, 12 million acres (4.9 million hectares) (17 percent) are severely saline and 11.3 million acres (4.5 million hectares) (16 percent) are covered with saline patches (Tipton, 1959).

According to recent appraisals more than 17 million acres (6.88 million hectares) of agricultural land in the country have water table levels within 10 feet (3 meters) of the ground surface which is a potentially hazardous limit and about 8 million acres (3.24 million hectares) are seriously salt affected. (Irrigation, Drainage and Flood Control Research Council, 1975).

In 1954, modern approaches to waterlogging and salinity control were initiated under a technical assistance program in the United States International Cooperation Administration through investigations of ground water and salinity problems. These investigations led to the Salinity Control and Reclamation Projects (SCARP). A formal agreement for SCARP I was signed in 1957 and the project was completed in 1961. An expanded program of investigations was initiated with the founding of the Water and Power Development Authority (WAPDA) in 1958 and WAPDA was assisted from 1959 by the following consultants: Harza Engineering Co. International, General Consultants; Tipton and Kalmbach, Inc., consultants in connection with reclamation work in the Punjab; and Hunting Technical Services, Ltd., and Sir M. MacDonald and Partners, consultants in connection with reclamation work in Sind.

Two activities created further intensification of investigations of the irrigation system in Pakistan. The first was the signing of the Indus Basin Treaty in January 1961 which divided the waters of the Indus between India and Pakistan. The second was a visit to the United States in July, 1961 by President Ayub, who requested and obtained assistance from President Kennedy for additional studies of waterlogging and salinity in Pakistan. The result of these two activities was the development of plans for utilization and transfer of Indus Basin waters in Pakistan and a detailed report on waterlogging and salinity with recommended solutions.

The 1959 and 1961 events combined to produce a series of inter-related and similar reports. The activities initiated by President Kennedy produced a report with an analysis of the problem and recommended solutions referred to as the Revelle (1964) Report. While the White House study was being conducted, Harza Engineering Company International, was preparing a similar but more comprehensive report in their capacity as general consultants to WAPDA (Hansen et al., 1963). As part of an agreement reached with WAPDA in 1962, Hunting Technical Services Limited and Sir M. MacDonald and Partners (1966) prepared a report known as "Lower Indus Report for the Sind...for the optimal development of water resources... and...for the control of waterlogging and salinity in these lands...". As part of the Indus Basin Treaty, the World Bank commissioned a study of the Upper Indus which began in 1964 and resulted in a detailed study and report for that area. This study, published in some detail by the consultants (Sir Alexander Gibb and Partners et. al., 1966), was also re-evaluated and published by the World Bank (Lieftinck, Sadove, and Creyke, 1968). Tipton and Kalmback (1967) published their development plan for the northern Indus with heavy emphasis on future development, including a continued SCARP program. The results of hydrologic studies of ground water and salinity made by the United States Geological Survey have also been published as multivolumed water supply papers and their studies also included an analysis of the problems caused by canal irrigation (Greenman, Swarzenski, and Bennett, 1967).

Basic Assumptions of Previous Studies

The problems diagnosed by each of these separate groups and the recommendations for solutions were quite similar. The "Lower Indus Report" and the study sponsored by the World Bank involved extensive and intensive studies in the field of farmer practices and field problems. All of these previously cited reports emphasize the necessity for increasing irrigation water supplies. It is true even today that many areas need additional irrigation water for maximum cropping intensity and maximum yields. WAPDA (1961), Hansen et al.(1963), Revelle (1964), Hunting Technical Services Limited and Sir MacDonald and Partners (1966), World Bank (Lieftinck, et. al. 1968), and

Tipton and Kalmbach (1967) each assumed that the problems of waterlogging and salinity and water supply augmentation would largely be solved by the SCARP tubewell program. The rationale upon which this was based is related to their analysis of what happens to water applied to the land by irrigation and is perhaps best quoted from Revelle (1964):

> Water applied to the land, either by irrigation or precipitation, was mostly lost through evapotranspiration, and never reached the water table except those relatively small areas where the ground water stood close to the surface.

This line of thought resulted in the assumption that most of the water applied to fields was stored in the soil and used by the crops. Recent data indicate a need to update and change this assumption. More insight into the details of the assumption can be obtained from this analysis as quoted from Hansen et al. (1963):

> For this preliminary analysis, we have assumed that farm losses and waste, deep percolation, and routine leaching will total 25 percent of the irrigation water delivered to the farms. This represents a farm efficiency of 75 percent. Such a high farm efficiency is possible in West Pakistan because the bund (border) system of irrigation is used throughout. The 25 percent is made up of evaporation and seepage from farm ditches, nonbeneficial evapotranspiration from ditch banks, water lost to the crops by percolation through the soil to levels below the plant roots due to uneven or excessive applications, low places in the fields, too slow a rate of application, uneven soil permeability, etc.; and waste due to failure or overtopping of the bunds, failure to stop irrigation at the proper time, or other operational factors.
>
> The requirements for the passage of water through the crop root zone to flush down salts brought in by the irrigation water (leaching requirement) has been kept in mind in adopting a farm irrigation efficiency of 75 percent. The water application needed for this purpose varies with the nature and concentration of dissolved salts in the irrigation water. An allowance of 10 percent of the irrigation water as the average leaching requirement is reasonable for the waters available for use in the Indus Plains. The leaching component does not have to be applied during each irrigation but can be accomplished by over-irrigation of rabi crops. This will permit limiting the water delivery requirements to the bare minimum (farm irrigation efficiency of 85 percent on most of the area

> cropped during the months of high demand. This would minimize difficulties due to limitations on canal capacities... Losses in watercourses have been estimated as 10 percent of the amounts delivered to them from canals or tubewells.

Similar conclusions, based on similar assumptions and logic, were also reached in the other studies. Table 1 was prepared from statements in these reports concerning the effectiveness of water use from the canal outlet (mogha) through the farmer's field.

The day-to-day farmer practices were studied and discussed in the extensive volumes prepared by Sir Alexander Gibb and Partners et al., (1966). However, they state:

> It is unfortunate that no measurement could be made of water channel losses on the watercourse. This has meant in practice that we can only show the total water available to a watercourse and the manner in which that quantity was allocated to the crops grown. It is not possible to state the amount of water received by the crops.

The lower Indus study (Hunting Technical Services Limited and Sir M. McDonald and Partners, 1966) also involved a detailed study of farmer practices in Pakistan. The primary conclusions related to farm water management are given as follows:

> Bearing in mind the deficient applications in some areas present overall efficiencies lie somewhere between 50 and 60 percent. For optimum yield they are nearer the former figure. Efficiencies are low at present owing to inadequate plant populations, poor field leveling and bund maintenance and general lack of attention to water distribution in the canals. Farmers tend to make over-frequent applications when water is freely available and sometimes unnecessarily late applications when the crops are mature and do not need water.
>
> Various figures are quoted for farm efficiencies in the literature. Experimental work on level contour borders yield an efficiency of 66 percent in the United States. Basin irrigation as practiced in Pakistan should be slightly more efficient than this with the same management practices. Messrs. Harza Engineering Company International has adopted a figure of 67.5 percent for the Northern Zone and it is therefore proposed to adopt this figure for the Region for the ultimate future in order that water requirement calculations for both zones are on the same basis.

Some measurements of water past the mogha were made. The report suggested that wastage of water did occur and farm efficiencies were much lower than the 50-60 percent reported. These lower efficiencies apparently, however, were not measured.

The data in Table 1 are the values for efficiencies used to plan and implement the SCARP programs in Pakistan. If these values for efficiencies are valid, then they should be near the values measured on SCARP watercourses today. SCARP 1 was in operation in 1961 and some of the studies on which additional SCARP programs were based were conducted on supplemented watercourses.

The high efficiencies given in Table 1 indicate that these reports and studies of the irrigation system of Pakistan were based on the assumption that farmers were doing a good job of irrigating. All the reports were uniform in this regard. In the summer of 1962 a team of consultants (Hansen, Bower, and Williams, 1963) to Harza made the following recommendations:

> The magnitude of irrigation efficiency is not only extremely variable but difficult to appraise for the future. Even though consumptive use is calculated with considerable accuracy, the water requirement to the field involves application efficiency. The losses occurring in conveyance must also be considered when determining diversion requirements.
>
> Thus, it is important that sufficient field studies be conducted to obtain a reasonable estimate of the water application efficiency that can be expected under different cropping conditions. Likewise, the losses in conveyance by seepage, evaporation, and plant use should be determined for the entire water distribution system.

This advice was evidently too late to be of use in the preparation of the reports. Since most of the water applied to fields was assumed to be consumptively used by the crops, the solution to on-farm water management problems was simply to provide more water. The actions for implementation of these programs was more tubewells and dams.

RECENT STUDIES

Watercourse Losses

Losses along the watercourse from the mogha to the field are high in Pakistan, expecially on tubewell augmented watercourses, as discovered during the past three years by the Colorado State University

Table 1. Water Loss Estimates from the Canal Outlet through the Farmer's Fields as Assumed by Various Studies.

Source	E_i	E_c	E_a
Lower Indus	67.5 (although the measured value was 50-60)		
Revelle Report	85*		
Harza	68	90	75
Tipton & Kalmbach	70	90*	78*
Gibb	65		
World Bank	63	90	70

E_i = irrigation efficiency = $(\frac{E_c}{100} \cdot \frac{E_a}{100})\ 100$

E_c = water conveyance efficiency = $(W_c/W_{co})\ 100$

E_a = water application efficiency = $(W_{et}/W_a)\ 100$

W_c = volume of water delivered by the conveyance system

W_{co} = volume of water delivered to the conveyance system

W_{et} = volume of irrigation water stored in the soil and removed by evapotranspiration.

W_a = volume of water applied to the area $W_a = W_c$

*Derived from statements or calculations.

Field Party stationed at Islamabad, Pakistan. These losses (seepage, wastage, and evapotranspiration by non-beneficial plants) frequently range from 25 to more than 50 percent of the flow at the mogha. Seepage is considered here to be that water which infiltrates from the channel cross section down into the soil profile and eventually to the water table. Wastage is the loss occurring to the ground surface either by overtopping, slow seepage through the side, breakage of the bund at nakkas or weak areas and operational losses. Evapotranspiration is that lost to the atmosphere. Corey and Clyma (1973) have detailed many of the physical causes for watercourse wastage. These include leaky nakkas, inadequate hydraulic capacity, thin channel walls, channels below ground, inadequate freeboard, obstructions such as trees, weeds, debris and sediment, poor alignment, and an excessive ditch system required to serve the many small fields.

Clyma, Arshad and Ashraf (1974) have presented data from flow measurement on watercourses and have shown that seepage may range from 0.3 to 35 m^3/sec per million square meters of watercourse perimeter, and wastage in many instances exceeds the seepage. They found that water delivery efficiencies range between 50 and 90 percent with an average near 60 percent for many SCARP watercourses. An additional disadvantage of wastage is that the greatest loss occurs when the farmer needs are the greatest. Since a SCARP tubewell frequently doubles the flow when added to the canal water already in the channel, wastage will increase. The period of peak water use is when the tubewell is operated. Crop yields are greatly reduced if excessive moisture stress occurs during the peak water use period.

Adequate data are not yet available to precisely quantify delivery losses under all conditions. In truth, each watercourse will have its own combination of sources of loss which will have to be enumerated individually when a water management program is applied. Some generalization however is possible.

A growing body of evidence suggests that on a 160 hectare, 1 cfs/350 acre (approximately 0.25 liters per second per hectare), "normal" watercourse, delivery losses will average 25 percent of the mogha discharge. This loss can be approximately subdivided into 10 percent seepage and 15 percent spillage of various types. There is, however, a very different water loss situation in SCARPs. With both tubewell and canal water flowing, losses have been repeatedly measured at an average of 40 percent, approximately 15 percent due to seepage and 25 percent due to spills (Eckert, Dimick,and Clyma, 1975). Where private tubewell water is added to canal flow the loss situation is often nearly the same as in SCARP watercourses.

It should be emphasized that these figures are averages of a variable situation. In all watercourse categories there will be a range of actual loss figures among different individual watercourses. In many cases, losses will be higher than average and the resultant potential benefits of preventing losses will be accordingly higher. In other instances, the situation will be reversed.

Irrigation Application Efficiencies

Application of water in the field is usually very inefficient in Pakistan. Table 2 presents data from Clyma, Arshad and Ashraf (1974) on measured field application efficiencies. Almost three-fourths of the measurements gave efficiencies of less than 30 percent and over one-half of the measurements resulted in efficiencies of less than 20 percent. These low efficiencies are a function of many factors and Corey and Clyma (1973) and Clyma, Arshad and Ashraf (1974) have discussed these factors in detail. Primary among these are unleveled fields, an irrigation canal delivery system that supplies water at a constant rate independent of the needs of the crop and a lack of knowledge by the farmer about the water requirements of his crop. Some under-irrigation does occur. Three instances of under-irrigation were obtained in 54 measurements. The common practice appears to be over-irrigation resulting in average field application efficiencies of near 20 percent.

WATER MANAGEMENT PROGRAM

Water supplies created by development of additional reservoirs or tubewells will effectively add little water for growing crops unless something is done to improve delivery and application efficiencies. The greatest increase in water supply can come from rehabilitation of watercourses to reduce delivery losses and improvement of field application efficiencies through land leveling and adjustment of irrigation to more nearly meet the requirements of crops. This increase in the effective use of water would result in reduced waterlogging since inefficient use of irrigation water is the cause of waterlogging and ultimately of salinity in Pakistan. Increased food production would also result because of increased yields and the increased area which could be irrigated with the water saved (Clyma and Corey, 1974).

The present average cropping intensity over the irrigated area of Pakistan is undoubtedly not more than 75 percent, less than one crop per year. The climatic resource is such that two or three crops or a cropping intensity of from 200 to 300 percent is possible. Water, however, is one of the limiting resources; yet an intensity of at least 150 percent is feasible with proper management. Of course, water is not the only input needed to increase acreages, but certainly the effective cropped acreage can be greatly increased with a coordinated water management program. There is, of course, the added benefit that better management also increases yields. This improvement can be accomplished within the present irrigation distribution system which although rather rigid does have advantages which can be utilized (Clyma and Corey, 1974).

Table 2. Irrigation application efficiencies observed at Mona on traditionally farmed fields (from Clyma, Arshad and Ashraf, 2).

Application Efficiency* Interval (Percent)	Crop				Total for Interval	% of Total Number of Observations	
	Wheat	Sugarcane	Fodders	Misc.		Interval	Accum.
0 ≤ 10	2	4	4	3	13	20	20
10 ≤ 20	8	5	2	2	17	26	46
20 ≤ 30	2	8	4	2	16	25	71
30 ≤ 40	2	2	3		7	11	82
40 ≤ 50		1		1	2	3	85
50 ≤ 60			2	1	3	5	90
60 ≤ 70		1			1	2	92
70 ≤ 80							
80 ≤ 90							
90 ≤ 100		4	1		5	8	100
Total	14	25	16	9	64	100	

*Application efficiency = $\frac{\text{amount of water stored in the root zone}}{\text{amount of water applied to the field}}$

One of the important elements in the new strategy for agricultural development in Pakistan is attention towards efficient water utilization and its proper management on the farm. Along with the new improved varieties of seed, the increased agricultural inputs, farming and irrigation practices must be modernized. The irrigation watercourses are, in general, inadequate for proper division and distribution of water among the irrigators.

Drainage is lacking in most of the country. Water is being lost by seepage, which results in building high water tables and salt accumulation on the ground surface. In failing to take complete responsibility for distribution of the water supplies to the farm fields, problems of waterlogging and salinity have resulted. Also, the expansion of the project areas, or cropping intensities, beyond the accommodation of the water supply facilities, and in some cases beyond the capability of the total water supply, has contributed to waterlogging and salinity problems.

One of the principal reasons that tubewells are popular is because they supply additional irrigation water. However, large portions of the tubewell discharge do not reach the farm fields because of high seepage losses in the watercourses. Thus, the lining of watercourses would result in 90-95 percent of the tubewell discharge reaching the farmer, rather than 50 percent in many cases.

Reducing watercourse seepage losses would also lower the water table. Since the principal salinity problems in the Punjab are in the central areas of the doabs, the lining of watercourses in these locations would be highly beneficial. In particular, those areas in Pakistan which have a high water table with very saline shallow groundwater would benefit most from a watercourse lining program. Although such a program would be very important to alleviating salinity problems, its popularity would primarily result from the additional water reaching the farmer's fields.

An even more important salinity control measure is reducing deep percolation losses from irrigated lands. More efficient irrigation practices would not only result in a lowering of the water table but would also allow either: (1) greater crop yields resulting from less soil moisture stress during critical growth periods; or (2) more land to be irrigated.

There are several technologies which, if adopted, would greatly improve irrigation water management in Pakistan. Full benefit can only be realized by adopting and utilizing all of them together. Irrigation water management is a system,and though any one practice has some benefits, full benefit comes only by adopting the entire system.

Given the magnitude of water losses now known to occur below the mogha, it is imperative that a water management program be launched to raise the efficiency with which water is used. Such a program has a greater potential for increasing the effective water supply and making a contribution to food production and rural incomes than perhaps any other agricultural development program.

An effective water management program must contain three elements: (1) watercourse improvement; (2) precision land leveling; and (3) irrigation and irrigated cropping extension. All deserve high priority. It should be emphasized, however, that if farmers continue their present irrigation and cropping practices, then the potential benefits from either watercourse improvement or precision land leveling are limited. Therefore, while extension and information transfer programs may be much more difficult to implement and their benefits harder to quantify than other components, it is essential that they receive just as much or more emphasis and full coordination within the overall program. In fact all three components are interdependent.

A coordinated balanced program is essential if Pakistan is to realize the full potential of increased food production that can result from improved water management practices and the consequent alleviation of waterlogging and salinity problems.

SUMMARY

There is a wide range in efficiencies of water delivery and water application in Pakistan. The above conclusions about water delivery and water application efficiencies are based on limited data and limited geographic sampling. An understanding of the hydraulic principles of water delivery and water application suggest that the results so far obtained generally represent the results that would be expected for most of Pakistan. Hunting Technical Services Limited and Sir M. MacDonald and Partners (1966) in their study of the Lower Indus suggested that somewhat similar results occurred there. Quantitative data were not presented, however.

The SCARP program objectives of reducing waterlogging and salinity by lowering the water table and increasing water supplies-both by pumping-are correct and worthwhile. The CSU Field Party has concluded, however, that: (1) farmers are not doing an efficient job of managing water from the mogha through their fields as has been previously assumed; (2) improving on-farm water management will make more water available for plant growth than any other similarly priced investment; and (3) hazards of waterlogging and salinity will be concurrently reduced.

REFERENCES

Clyma, Wayne, Arshad Ali and Mohammad Ashraf. 1974. Case Studies of Watercourse Losses in Pakistan. Colorado State University, Water Management Research Project/Pakistan.

Clyma, Wayne, Arshad Ali and Mohammad Ashraf. 1974. Irrigation practices and Application Efficiencies in Pakistan. Colorado State University, Water Management Research Contract/Pakistan. Water Management Technical Report No. 39.

Clyma, Wayne and Gilbert L. Corey. 1974. The Importance of Farm Water Management in Pakistan. Colorado State University, Water Management Research/Pakistan, Water Management Technical Report No. 38.

Corey, G. L. and Wayne Clyma. 1973. Improving Farm Water Management in Pakistan. Colorado State University, Water Management Research Contract/Pakistan. Water Management Technical Report No.37.

Eckert, J. B., N. Dimick, and W. Clyma. 1975. Water Management Alternatives for Pakistan: A Tentative Appraisal. Water Management Research in Arid and Sub-Humid Lands of Less Developed Countries, Water Management Technical Report No. 43, Colorado State University, Fort Collins, June.

Greenman, D. W., W. V. Swarzenski, and G. D. Bennett. 1967. Ground Water Hydrology of the Punjab, West Pakistan with Emphasis on Problems caused by Canal Irrigation. U. S. Gelogical Survey Water-Supply Paper 1608-H, U. S. Government Printing Office, Washington, D. C.

Hansen, V. E., C. A. Bower, and F. J. Williams. 1963. Salinity Control and Reclamation Program in the Lower Indus Basin: A Review Made during July and August 1962. Harza Engineering Company International, Lahore, West Pakistan, September.

Hunting Technical Services Limited and Sir M. MacDonald and Partners. 1966. Lower Indus Report. Part 1: Present Situation, a report prepared for WAPDA.

Irrigation, Drainage, and Flood Control Research Council. 1975. Country Report - Pakistan. International Conference on Waterlogging and Salinity, Lahore, Pakistan, October 13-17.

Khan, Qurban. 1974. Irrigation Management in Pakistan. Unpublished M. S. thesis, Colorado State University, Fort Collins, Colorado, January.

Lieftinck, Pieter, A. R. Sadove, and T. C. Creyke. 1968. Water and Power Resources of West Pakistan: A Study in Sector Planning. Vol. I - The Main Report. Published by the World Bank and the Johns Hopkins Press, Baltimore.

Mohammad, G. 1965. Waterlogging and Salinity in the Indus Plain: Rejoinder. Pakistan Development Review, Vol. 5, No. 3, Karachi.

Mohammad, G. and E. Beringer. 1963. Waterlogging and Salinity in West Pakistan. Pakistan Development Review, Vol. 3, No. 3, Karachi.

Mohammad, G. and E. Beringer. 1963. Waterlogging and Salinity in West Pakistan. Pakistan Development Review, Vol. 3, No. 2, Karachi.

Revelle, R. et al. 1964. Report on Land and Water Development in the Indus Plain. The White House, Washington, D.C. January.

Sir Alexander Gibb and Partners, International Land Development Consultants N.V. and Hunting Technical Services Limited. 1966. Programme for the Development of Irrigation and Agriculture in West Pakistan. Comprehensive Report. London and Arnhem, Vol. 7 and 10, May

Tipton, R. J. 1959. Irrigation and Drainage in West Pakistan. Annual Convention of ASCE in Washington, D.C. October.

Tipton and Kambach. 1967. Regional Plan, Northern Indus Plains: Development and Use of the Water Resources of the Indus Plain. A Report prepared for WAPDA, Volume I - Report.

Water and Power Development Authority. 1961. Programme for Waterlogging and Salinity Control in the Irrigated Areas of West Pakistan, Lhore, West Pakistan, May.

DESALINIZATION OF A HIGHLY SALINE SOIL, PREDICTION AND FIELD OBSERVATION

J. W. van Hoorn, J. Risseeuw and J. M. Jurado Prieto 1/

INTRODUCTION

The Marismas soils, located along the Quadalquivir River in southern Spain, are saline, heavy clay soils that are used for cattle grazing and, under natural conditions, often flooded during winter.

On the left bank reclamation schemes have been carried out since 1930, consisting of flood protection by dikes, drainage,and irrigation with river water. In these schemes leaching is left to the natural rainfall (Grande and Losada,1969).

On the right bank a geohydrological investigation, carried out by the Quadalquivir project with the assistance of the F.A.O., revealed the existence of fresh water in an aquifer below the thick clay layers that can be used for irrigation of part of the Marismas soils on that side of the river.

An experimental farm was set up in order to provide detailed information for the future reclamation and development of 16,000 ha of Marismas soils on the right bank.

In general these soils are much less permeable than those on the left bank. In a first stage special attention was paid to the tile drainage system to be applied and the duration of the desalinization period, which is scheduled before the installation of an irrigation system. For economical reasons the execution of the irrigation system in the 16,000 ha reclamation scheme should be phased in such a way that it could be used without delay for irrigating fodder crops.

NATURAL CONDITIONS OF THE EXPERIMENTAL SITE

Soil. The soil can be classified as a clay soil, having a clay fraction of 65%. The organic matter content is very low, approximately from 0.8 to 1% in the 0-25 cm layer, and decreasing with depth to 0.3% in the 50-75 cm layer. The mineralogical composition shows about 50% montmorillonite, 30% kaolinite, and 20% illite. The exchange capacity equals 30 to 40 me/100 g.

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The apparent density is about 1.35 g/cm^3, corresponding with a porosity of 0.50. Below a depth of 1.50 m the apparent density decreases to 1 g/cm^3. Field capacity corresponds with a moisture content of 38% by weight and wilting point with 23%, yielding an available moisture holding capacity of 15% weight or 20 mm for each 10 cm of soil.

The hydraulic conductivity is low, ranging from 0.05 to 0.1 m/day. Below a depth of 1.50 m the soil may be considered as impermeable.

The soil salinity is extremely high and increases to a depth of at least 2 m. For practical reasons the soil salinity is determined in the laboratory as the electrical conductivity of the 2/1 extract ($EC_{2/1}$) instead of the electrical conductivity of the saturated paste (EC_e). Since the moisture content of the saturated paste equals about 80% by weight, the $EC_{2/1}$ values should be multiplied by 2.5 for conversion into EC_e values. In autumn 1970, at the start of the investigations, the average salinity of the plots of the experimental farm was as follows:

Layer	0-25 cm	25-50 cm	50-75 cm	75-100 cm	100-150 cm	150-200 cm
$EC_{2/1}$, mmhos/cm	12	20	26	28	31	34

The SAR values of the 2/1 extract increase from 30 in the 0-25 cm layer to 50 in the 75-100 cm layer, which corresponds with an increase from 50 to 80 for the saturated paste. The principal ions are Na^+ (about 80%) and Cl^- (about 90%), the ion distribution being approximately the same as that of sea water. The pH equals 8.

The gypsum content is low, around about 0.3%. The soil contains, however, a considerable amount of fine graded calcium and magnesium carbonates, approximately 10% in the 0-25 cm layer, 20% in the 25-75 cm layer, and 25% in the deeper layer.

Climate. The climate is a Mediterranean climate with an Atlantic influence. The main characteristics can be summarized as follows:

	year	December-January	July-August
Temperature	18°C	10°C	27°C
Relative humidity	0.70	0.80	0.50
Bright sunshine	0.63	0.50	0.80

The evaporation from a free water surface (E_o), calculated according to the Penman formula, attains about 1400 mm per year, the daily average ranging from 1 to 1.5 mm/day in December and January and around 7 mm/day in July and August.

The mean annual rainfall equals 589 mm (period 1931-1970 for Sevilla-Tablada), showing the following distribution:

Month	J	F	M	A	M	J	J	A	S	O	N	D
Rainfall in mm	83	70	86	50	34	13	1	4	24	65	82	77

Prediction of the Desalinization. Two main cases can be distinguished with respect to the water and salt movement in the drainage and desalinization process.

(1) **Drains** located well above an impermeable layer. In this case the water movement, and consequently the salt movement, is essentially vertically downward in the unsaturated as well as in the saturated zone above drain level (figure 1).

(2) **Drains** located on an impermeable layer. In this case the water and salt movement are vertically downward in the unsaturated zone above the water table, whereas below the water table the horizontal component becomes quite important. This means that not all the water percolates the whole soil profile above drain level.

The difference between the two cases may be illustrated by a calculation of the desalinization, for which the soil profile will be considered consisting of 5 layers of 25 cm.

In the first case we can use the following formula, derived for a leaching process due to mixing of leaching water and soil solution (Molen, 1973)

$$C_t^N = C_i + (C_o - C_i)e^{-ft/T} \sum_{n=0}^{n=N-1} \frac{f^n t^n}{n!T^n}$$

C_t^N : salinity of layer N at time t, in g/l or mmhos/cm

C_i : salinity of irrigation water or rainfall

C_o : salinity of layer N at time t = 0

f : leaching efficiency coefficient

$T=V/Q$: time of residence or ratio between the volume of the system and the flux through the system

$ft/T=fQt/V$: ratio between the amount of efficient leaching water in mm at time t percolated through a layer containing V mm

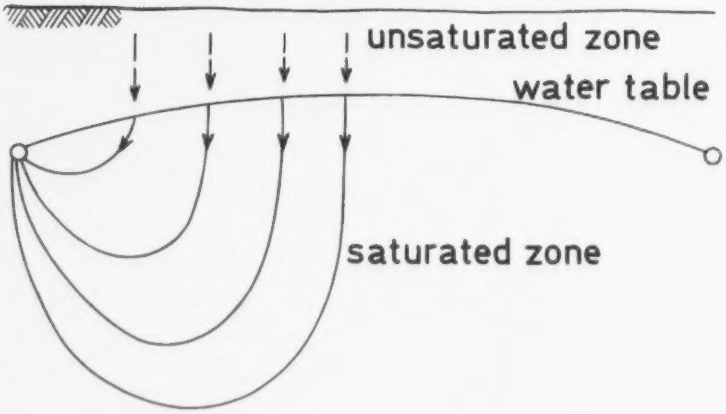
The desalinization was calculated assuming leaching by rainfall since, as mentioned in paragraph 1, the irrigation system would become operational after the salinity was lowered to such a level that irrigated summer crops could be grown with reasonable results.

The $EC_{2/1}$ values mentioned in paragraph 2.1 for autumn 1970 have been used as starting values for C_o. Since the C_o values differ for the successive layers, the principle of superposition was applied in this calculation. The salinity of the precipitation is considered negligible. The leaching efficiency coefficient, expressing the more or less complete mixing between leaching water and soil solution, is assumed equal to 1. This means that the desalinization is calculated for the most favourable situation yielding the lowest amount of leaching water. The result of the calculation is shown in figure 2.

In the second case the amount of water percolating vertically downward decreases with depth. Moreover, the amount of water passing through t

Figure 1

DRAINS LOCATED WELL ABOVE AN IMPERMEABLE LAYER


unsaturated zone
water table
saturated zone

DRAINS LOCATED ON AN IMPERMEABLE LAYER

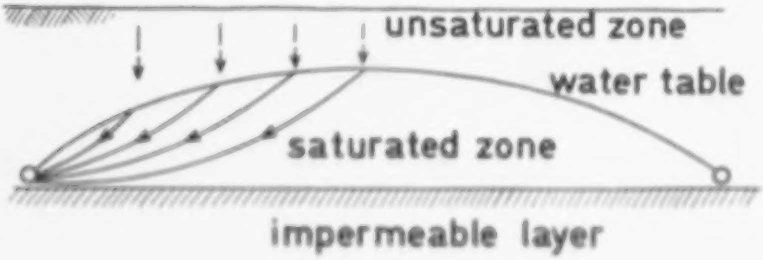
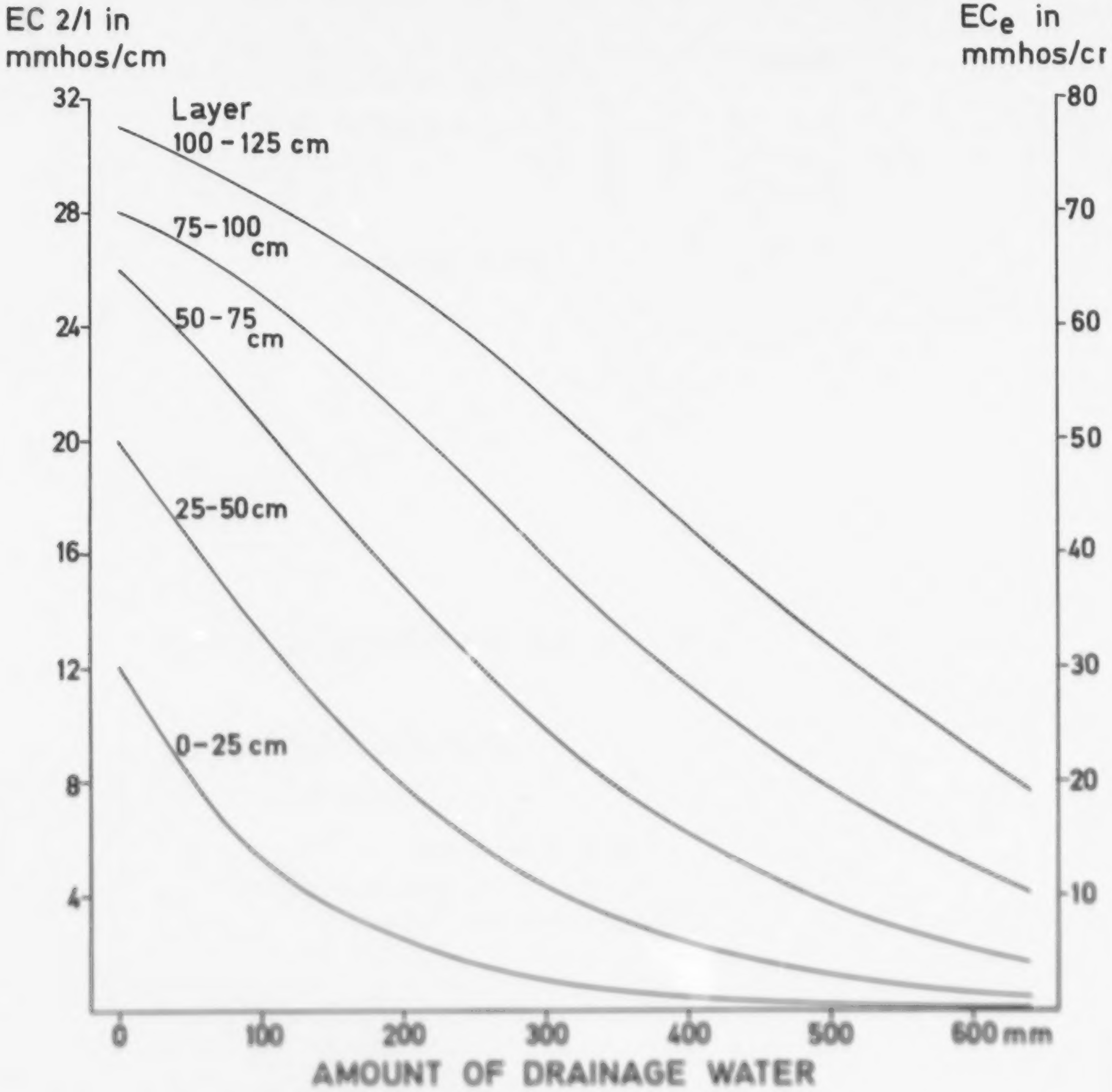

unsaturated zone
water table
saturated zone
impermeable layer

Figure 2

DESALINIZATION

(DRAINS LOCATED WELL ABOVE AN IMPERMEABLE LAYER)



soil profile in horizontal direction increases with decreasing distance towards the drain. So the situation with regard to leaching differs from the first case in vertical as well as in horizontal direction and will be complicated by the non-steady state nature of the groundwater flow.

For the calculation of the leaching process it was assumed that 100% of the water percolates the first layer (0-25 cm), 80% the second layer (25-50 cm), 60% the third layer (50-75 cm), 40% the fourth layer (75-100 cm) and 20% the fifth layer (100-125 cm), whereas no difference was made with respect to the horizontal distance from the drain.

The leaching process was calculated by a numerical method, which is based on the following principle (Van Hoorn et al., 1969; Molen, 1973; UNESCO, 1970). Since leaching starts with a mixing between irrigation or rain water at concentration C_i and the moisture of the first soil layer at concentration C_{s_1}, the concentration of the soil of the first layer after mixing, C_{x_1}, can be calculated in the following way:

$$\text{a mm of influent water } x C_i + \text{b mm of soil water } x \; C_{s_1} = (a+b) \; x \; C_{x_1}$$

If the amount of water retained in the first layer or drained off by horizontal flow is equal to c mm, an amount (a-c) having a concentration C_{x_1} percolates in depth and mixes with the moisture of the second layer. The concentration of the soil solution of the second layer after mixing, C_{x_2}, can be calculated in the same way:

$$(a-c)C_{x_1} + d_{C_{s_2}} = (a-c+d)C_{x_2}$$

The calculation was carried out for steps of 20 mm of precipitation, neglecting again the salinity of the precipitation. The results are presented in figure 3. A comparison between figures 2 and 3 shows that the desalinization of the deeper layers is much lower in the second case as the amount of percolation water decreases gradually with depth.

The salinity expressed as $EC_{2/1}$ in mmhos/cm, can be converted to tons of salt per ha for the Marismas soils with the following formula:

$$S = 0.7 \; EC \times SP \times AD \times D \times \frac{1}{1000}$$

S : salinity, expressed in T/ha
EC : salinity, expressed in mmhos/cm
SP : saturation percentage, 200 gr of water per 100 gr of soil for the 2/1 extract
AD : apparent density, 1.35 g/cm^3
D : thickness of the layer in cm

Figure 4 shows the quantities of salt leached in both cases. As the soil is impermeable below a depth of 1.30 m and the drains are located at a depth of 1.40 m, the calculation for the second case may be considered as a better approximation than the first calculation.

From Figure 3 we may estimate the length of the period necessary to obtain a salinity level that allows growth of irrigated summer crops such as maize

Figure 3

DESALINIZATION
(DRAINS LOCATED ON AN IMPERMEABLE LAYER)

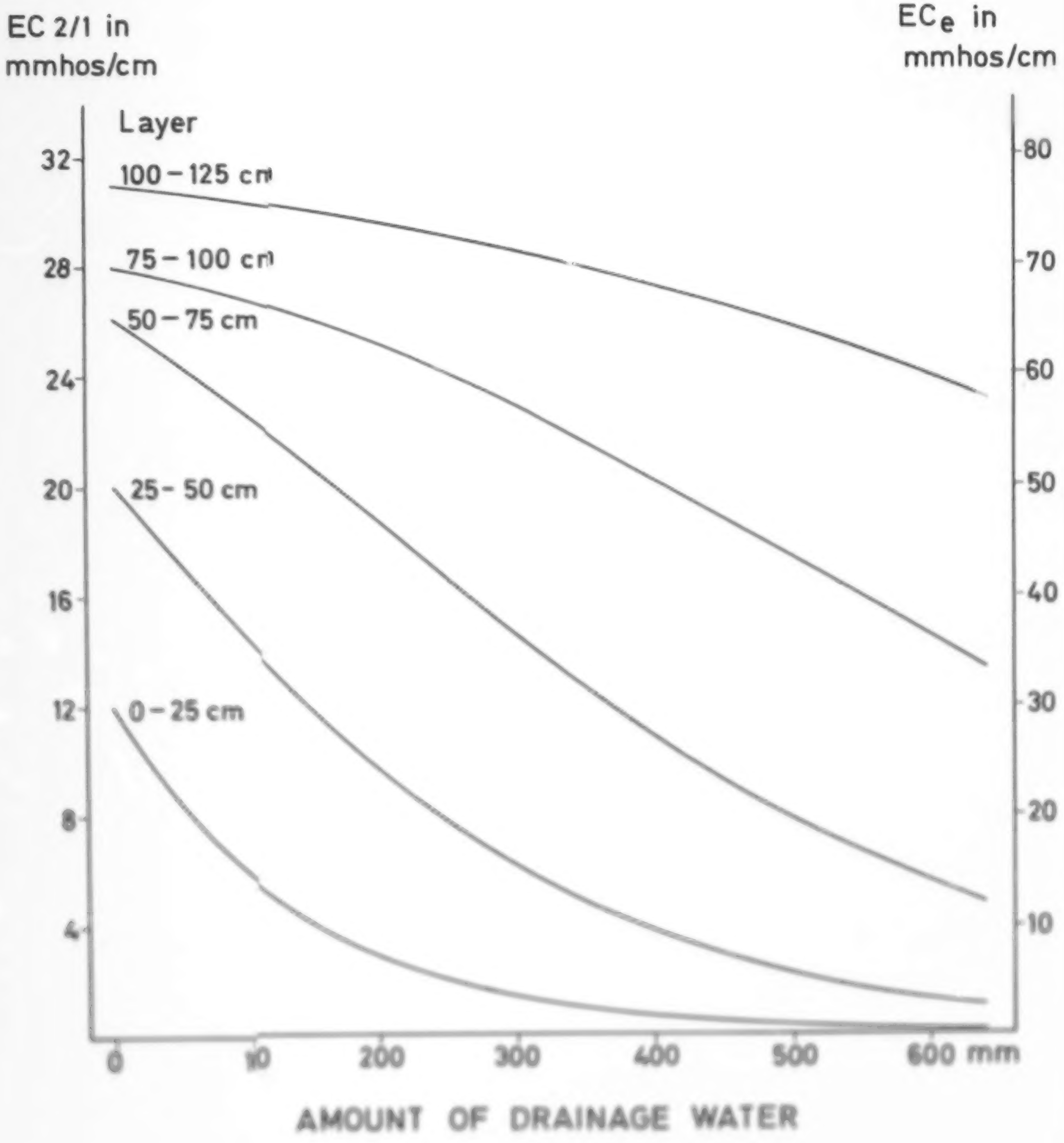
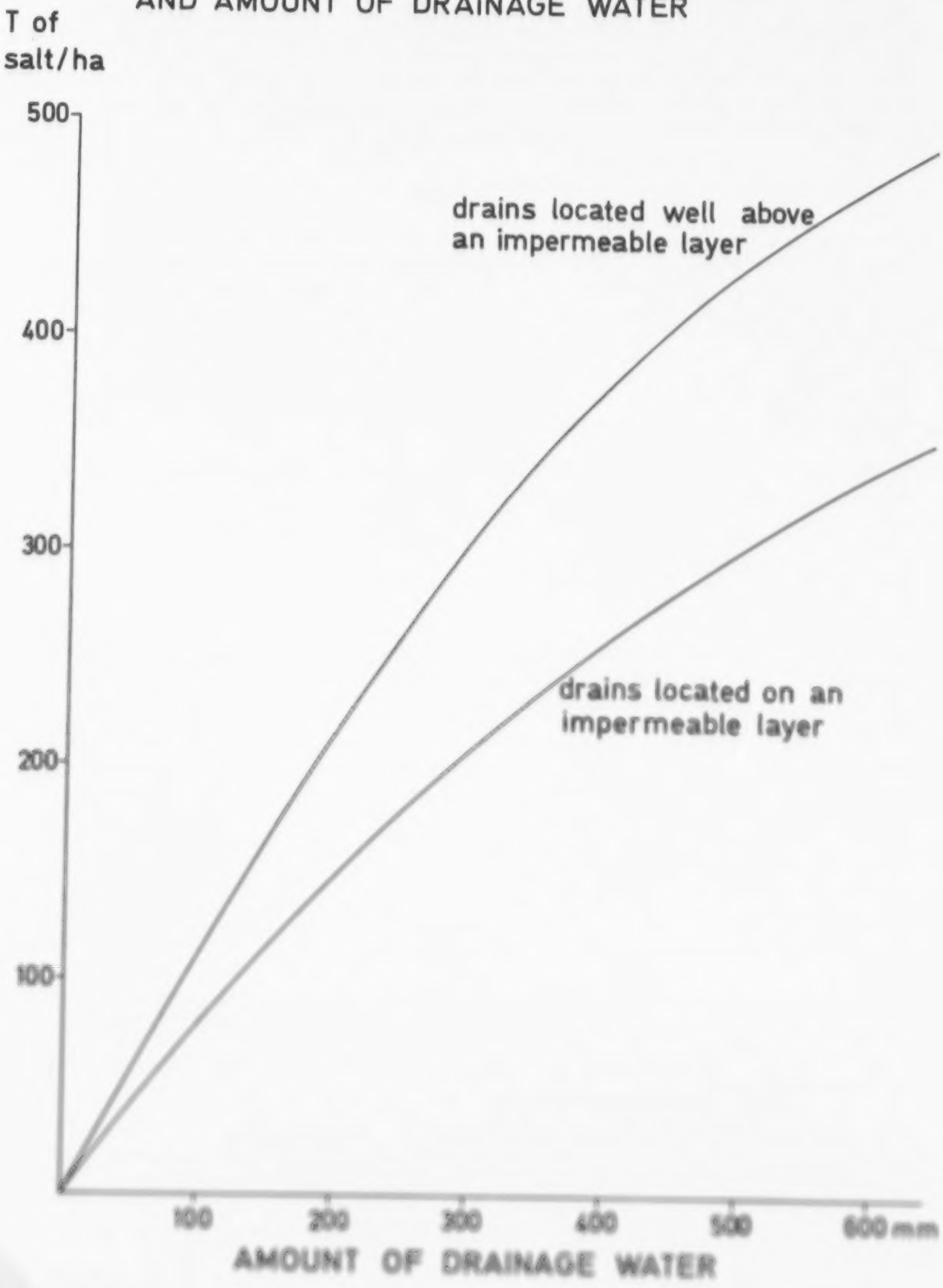


Figure 4

RELATION BETWEEN QUANTITY OF SALT REMOVED AND AMOUNT OF DRAINAGE WATER



and fodder sorghum with reasonable yields. If we take for this salinity level an EC_e value of 5 in the 0-50 cm layer, the amount of water drained off through the soil profile should be in the range from 400 to 500 mm. If, moreover, we estimate the average amount of drainage water during winter from 80 to 100 mm, which is about 20% of the rainfall, it would take approximately 5 years to obtain a reasonable salinity level for growing irrigated summer crops.

FIELD OBSERVATIONS

Part of the experimental farm was tile-drained at a depth of 1.40 m and with a length of 200 m. Using the Dumm formula for transient flow and introducing a hydraulic conductivity of 0.1 m/day, a storage coefficient of 0.03 and, as drainage criterion, a drawdown of 25 cm in two days after the water table had risen to the surface due to heavy rainfall, a spacing of 14 m was calculated. The tiles were spaced at 10, 20 and 40 m in replicates. The spacing of 40 m, although too wide, was chosen in order to obtain a greater range of spacings for studying drainage and desalinization, and was reduced to 10 m after three years of observation.

Drain discharges and water tables were measured regularly throughout the year, water samples being taken at every measurement of drain discharge. Soil samples were taken midway between the tiles four times a year, in March, June, September, and December. Moreover soil samples were taken once a year at several locations between the tiles: at 2 and 5 m from the tile for a spacing of 10 m; 2 , 5 and 10m from the tile for a spacing of 20m; and at 2, 5, and 20 m for a spacing of 40 m.

Amount and Salinity of Drainage Water and Quantity of Salt Removed. Table 1 presents for 4 years the amounts of drainage water due to rainfall during autumn, winter, and spring. A comparison of the four years shows that the amount of drainage water depends upon the yearly amount of rainfall and its distribution. The rainfall from December until the end of March has a strong bearing on the amount of drainage water, especially the rainfall in December and January. During those months the evapotranspiration ranges between 1 and 1.5 mm/day, whereas it increases to about 2.5 mm/day in February and March. The rainfall in April and May is only of slight importance for the amount of drainage water. Autumn rainfall replenishes the moisture deficit of the soil so that the winter rainfall becomes efficient for leaching. The start of drain discharge was observed after approximately 120 mm of rainfall, if the discharge started before January, and after about 150 mm of rainfall, if the discharge started during January.

Table 1 shows also a pronounced decrease in the amount of drainage water with increasing spacing. In the case of a larger spacing the water table rises to a higher level during rainfall and falls more slowly, which may cause a larger surface runoff at first and afterwards a higher loss due to evapotranspiration.

Table 2 shows that the average salinity of the drainage water is higher in the case of a narrower spacing, because the water table is generally lower and more water flows through the deeper and more saline layers

Table 1. Precipitation and amount of drainage water

Period	1931 - 1970	1970 - 1971				1971 - 1972				1972 - 1973				1973 - 1974			
	prec. in mm	prec. in mm	dr. in mm			prec. in mm	dr. in mm			prec. in mm	dr. in mm			prec. in mm	dr. in mm		
			10	20	40		10	20	40		10	20	40		10	20	
Sept.	24	0				0				24				0			
Oct.	65	45				0				186				13			
Nov.	82	32				8				55				56			
1.9 - 1.12	171	67	0	0	0	8	0	0	0	265	93	37	26	69	0	0	
Dec.	77	101				40				123				79			
Jan.	83	104				123				60				38			
Febr.	70	2				74				9				29			
1.12 - 1.3	230	207	93	59	27	237	35	22	15	192	108	102	68	147	17	7	
March	86	42				109				47				84			
April	50	168				10				4				81			
May	34	62				18				62				0			
1.3 - 1.6	170	272	16	13	12	137	28	22	9	113	9	4	4	165	31	28	
TOTAL	571	556	109	72	39	382	63	44	24	570	210	143	98	381	48	35	

Table 2. Average salinity of drainage water in g/l

Period	10 m.	20 m.	40 m.
1.12.70 - 1.6.71	59	55	48
1.12.71 - 1.6.72	64	64	54
1.09.72 - 1.6.73	59	47	41
1.12.73 - 1.6.74	59	56	--
average	60	55	48

Table 3. Quantity of salt removed in T/ha

Period	10 m.	20 m	40 m
1.12.70 - 1.6.71	65	40	19
1.12.71 - 1.6.72	40	28	13
1.09.72 - 1.6.73	126	68	40
1.12.73 - 1.6.74	28	20	--
total	259	156	72

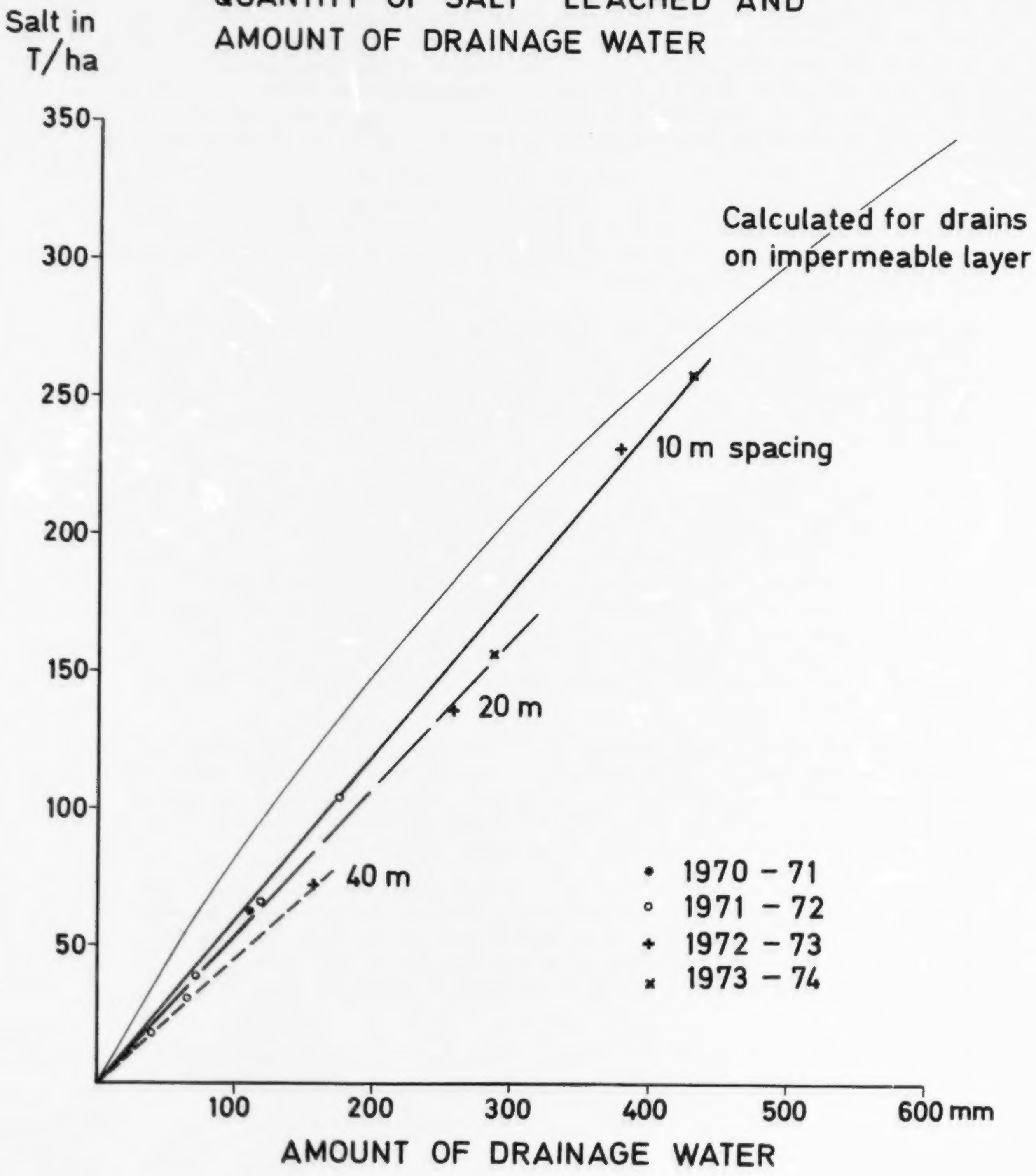
towards the drains. For each drain spacing the observations also showed that the salinity of the drainage water decreased with increasing drain discharge and water table.

The influence of spacing on the amount and salinity of drainage water causes an increase of the quantity of salt removed from the soil profile with decreasing drain spacing, as shown in table 3. The quantities of salt have been calculated from the observed drain discharges and the corresponding salinity of the drainage water.

Figure 5 presents the relation between the amount of salt leached out of the soil and the amount of drainage water. Whereas the calculated relation is curvilinear, the observed ones seem to be rectilinear. After four years the observed amount of removed salt for the 10 m spacing is almost equal to the amount calculated for the case of drains located on an impermeable layer under the assumption of a gradual decrease of percolation water with depth.

Figure 5

QUANTITY OF SALT LEACHED AND AMOUNT OF DRAINAGE WATER



According to figure 3 an amount from 400 to 500 mm of drainage water would be required to attain an EC_e value of about 5 mmhos/cm in the 0-50 cm layer, sufficiently low to grow irrigated summer crops. This corresponds to the removal of 250 to 300 tons of salt per ha. Utilizing this criterion and the observations after 4 years, the length of the desalinization period can be estimated at 4, 7, and 12 years respectively for drain spacings of 10, 20, and 40 m. The rainfall during these four years was more or less equal to or below the average of the period 1931-1970, as is shown by Table 1.

Results of an Irrigation Trial. From the start of the operation an irrigation system was available for experimental reasons in order to grow crops under saline conditions and to investigate whether leaching could be speeded up by applying irrigation water.

In summer 1972 a plot, drained at a spacing of 15 m, was selected for an irrigation trial. On one part sprinkler irrigation was used with three applications every 10 days, the application being stopped as soon as water splashes appeared on the surface. On the other part surface irrigation was applied, also with three waterings at an interval of 5 to 10 days. The results are summarized in Table 4.

In the case of sprinkling, 9 mm of water were drained off and 9 tons of salt per ha removed after a total water application of 197 mm. Most of the water applied was used for replenishing the soil and for evaporation during that period. In the case of surface irrigation 90 mm of water were drained off and 17 tons of salt per ha removed after a total water application of 462 mm. In the first case the average salinity of the drainage water was 82 g/l, whereas in the case of surface irrigation it was only 19 g/l. This difference confirms the observations after rainfall that the salinity of the drainage water decreases with increasing heights of the water table and drain discharge.

In the case of surface irrigation the first application was the largest one and produced moreover the highest percentage of drainage water, about 20%, due to a higher infiltration rate. For the third application the percentage of drainage water was approximately 15%, with a discharge of about 2.5 mm/day and a removal of 0.5 tons of salt per ha per day.

Assuming that the soil structure and the infiltration rate will not deteriorate due to prolonged surface irrigation so that a drain discharge of 2.5 mm/day is maintained, removing 0.5 tons of salt per ha, the application of surface irrigation would ask for 500 to 600 days in order to drain off from 1250 to 1500 mm of water and to remove from 250 to 300 T/ha.

However, there is a strong possibility that soil structure and infiltration rate may deteriorate during such an operation, so that the length of the desalinization period will increase.

Table 4. Results of a leaching trial with irrigation water

Sprinkler irrigation

Period	3.7-12.7	13.7-22.7	23.7-1.8	3.7-21.9
Irrigation water, mm	48	65	84	197
Drainage water, mm	0.3	1.4	5.7	9.0
Salinity of drainage water, g/l	101	80	68	82
Salt removed, T/ha	0.3	1.1	3.4	7.4

Surface irrigation

Period	3.8-12.8	13.8-16.8	18.8-24.8	3.8-22.9
Irrigation water, mm	240	125	97	462
Drainage water, mm	56.7	14.3	14.0	90.3
Salinity of drainage water, g/l	15	20	22	19
Salt removed, T/ha	8.7	2.8	3.0	16.9

According to the results of this trial it does not seem interesting for this heavy soil of low permeability to replace the natural desalinization process due to rainfall by an artificial one applying irrigation water. From a technical point of view the best use of irrigation water would be probably by applying it in autumn in order to replenish the soil, so that a higher percentage of the rainfall afterwards may be drained off.

Soil Analysis. Table 5 summarizes the results of the analysis of soil samples taken at increasing distance from the tile drains. In general soil salinity decreases towards the drain, although this is sometimes masked by the heterogeneity of the soil. Moreover, Table 5 shows the $EC_{2/1}$ values calculated from the amounts of salt removed. In spring 1971 a quantity of 64.5 T/ha was leached out in the case of a 10 m spacing. If we suppose that the desalinization takes place according to the assumptions used for the theoretical calculation in paragraph 3, this amount of 64.5 T/ha corresponds with a decrease of the $EC_{2/1}$ value in the 0-25 cm layer from 12 to 6.7, in the 25-50cm layer from 20 to 15.5, in the 50-75 cm layer from 26 to 23.3, and in the 75-100cm layer from 28 to 27.1. The calculated values range between the observed ones, excepted for the 10m spacing in spring 1973.

Table 5. Observed soil salinity ($EC_{2/1}$ in mmhos/cm) at increasing distance from the drain and calculated value.

Layer	10 m spacing			20 m. spacing				40 m. spacing			
	Observed		Calc.	Observed			Calc.	Observed			Calc.
	2m	5m.		2m	5m	10m		2m	5m	20m	
Spring 1971											
0-25	4,2	6,3	6,7	3,5	4,0	10,8	8,7	3,8	4,8	11,6	10,2
25-50	14,3	17,6	15,5	9,8	12,0	19,3	17,5	7,3	11,5	16,4	18,8
50-75	23,0	24,7	23,3	23,5	23,8	30,1	24,5	16,7	20,3	23,8	25,4
75-100	28,4	30,0	27,1	28,4	25,8	28,7	27,5	22,0	26,1	29,5	27,8
0-100	17,5	19,6	18,1	16,3	16,4	22,2	19,5	12,5	15,7	20,3	20,5
Spring 1972											
0-25	4,7	6,3	4,0	2,7	5,2	7,9	5,9	2,5	6,4	12,4	8,7
25-50	10,8	11,5	11,7	7,3	12,7	11,5	14,4	9,2	11,7	15,0	17,6
50-75	21,0	22,7	20,5	18,6	23,2	22,6	22,5	16,4	21,8	22,7	24,5
75-100	27,1	30,2	25,9	25,4	30,2	28,3	26,8	25,4	28,2	27,8	27,6
0-100	15,9	17,9	15,5	13,5	17,8	17,6	17,4	13,4	17,0	19,5	19,6
Spring 1973											
0-25	2,3	2,3	0,6	1,6	3,1	3,2	2,9	2,0	4,1	6,8	5,9
25-50	6,2	7,6	3,6	9,4	9,2	5,6	9,6	2,0	6,3	13,6	14,4
50-75	18,8	16,1	10,5	12,7	20,3	16,2	18,5	9,1	14,7	22,8	22,5
75-100	24,6	23,8	19,8	21,7	25,8	25,8	25,0	18,9	20,3	30,4	26,8
0-100	13,2	13,0	8,6	11,4	14,6	12,7	14,0	8,0	11,4	18,4	17,4

Figure 6

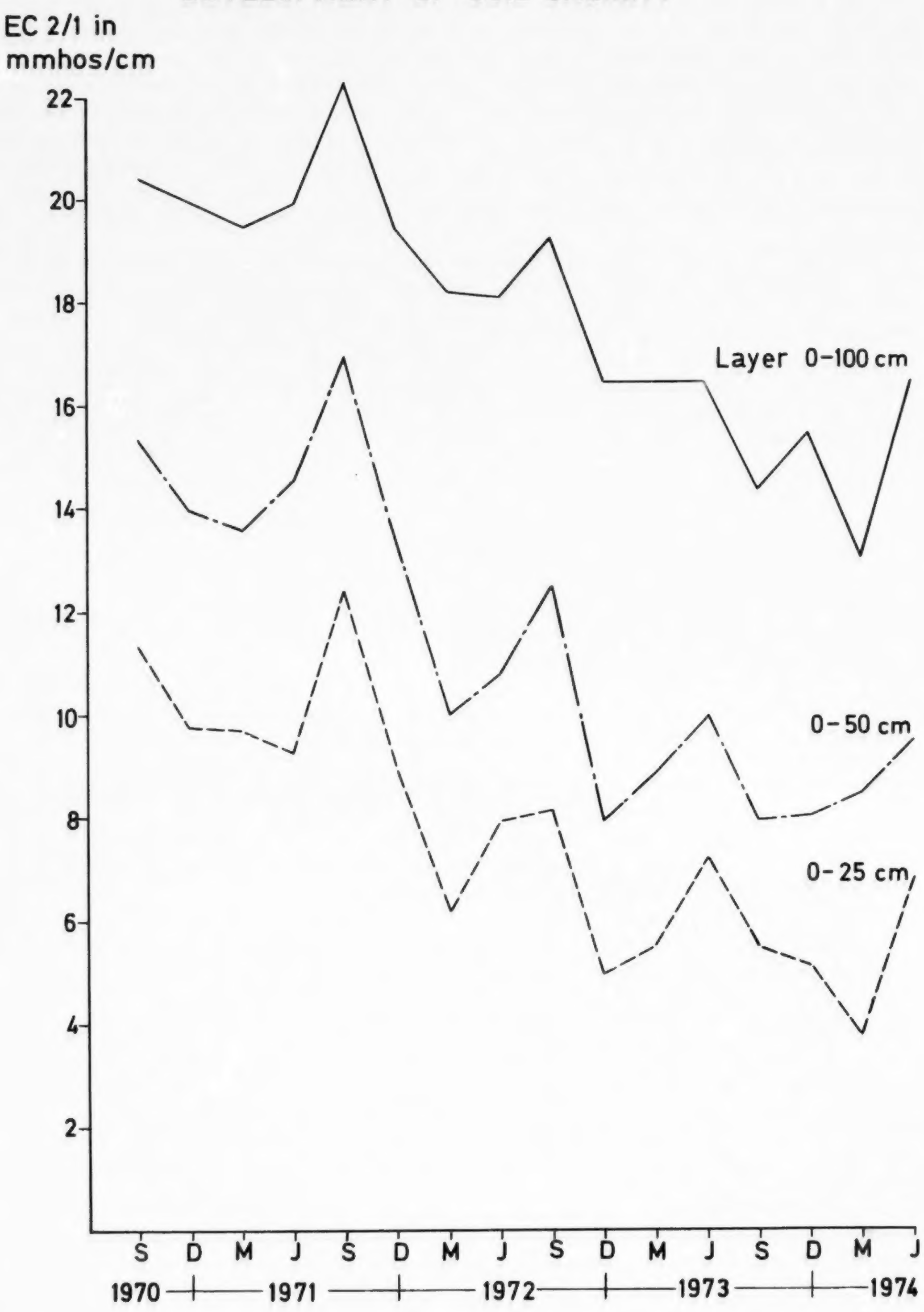

DEVELOPMENT OF SOIL SALINITY
EC 2/1 in mmhos/cm
22
20
18
16
14
12
10
8
6
4
2
Layer 0-100 cm
0-50 cm
0-25 cm
S
D
M
J
S
D
M
J
S
D
M
J
S
D
M
J
1970
1971
1972
1973
1974

Figure 6 shows the development of soil salinity at successive dates for the spacing of 10 m. In general soil salinity is decreasing, however with short-term increases. This may be attributed to the heterogeneity encountered in a very saline soil and to capillary rise of salts from the underlying layer. Since the $EC_{2/1}$ value ranges between 30 and 35 in the 100-150 cm layer, a small amount of capillary rise may already cause a considerable increase of soil salinity in the 0-100 cm layer during summer, e.g., the increase of the $EC_{2/1}$ value from 18.1 to 19.3 between June and September 1972 can be explained by a capillary rise of about 15 mm.

In reality the desalinization process occurs in a way that differs from that assumed for the calculation. This may be ascribed to differences in vertical and in horizontal flow through the soil profile, causing a decrease of salinity towards the drain, and to capillary rise, causing an increase of salinity in summer. However, Figure 5 has shown that for spacings of 10 and 20 m the calculation assuming a decrease of percolation water with depth yields a reasonable approximation of the total amount of salt removed.

LITERATURE

Grande, R. and A. Losada. 1969. The drainage systems of the Quadalquivir River delta, its operation, maintenance and evolution. Transactions 7th Congress I.C.I.D. : 25.169-25.179.

Van Hoorn, J. W., et al. 1969. Leaching efficiency. International Conference on Arid Lands in a Changing World, University of Arizona.

Molen, W. H. van der. 1973. Salt balance and leaching requirement. Drainage Principles and Applications, vol. II : 59-100.

UNESCO. 1970. Research and training on irrigation with saline water. Technical report of UNDP project Tunisia 5.

SYSTEM FOR MANAGING SALINE AND RUN-OFF WATER FOR FRUIT AND CROP PRODUCTION IN ARID REGIONS OF MEXICO

Sampat A. Gavande, Brent C. Cluff and Nazir Nahlawi[1/]

INTRODUCTION

More than 52% of the cultivable area of Mexico is classified as arid and semi-arid. Nearly half of this area, particularly in the northern states is extremely arid and presents some salinity, alkalinity, and waterlogging problems. Groundwater, when available for irrigation, is often saline or moderately saline-sodic.

The soils of the north are calcareous and contain some salts and exchangeable sodium. They also have a subsurface horizon rich in carbonate and compact, usually at about 30-90 cms below the ground surface.

Before planning a major irrigation system for crop production, provision for drainage and leaching of salts is often recommended for this region. Good quality water from underground sources is rarely available for leaching salts, and when available pumping costs are prohibitively expensive. It has been pointed out in the past that such lands could be used to harvest water. In fact, rudimentary water harvesting systems have been established by local people in some parts of this area.

Thus, with the need for integral land use and soil reclamation in mind, a multipurpose water use and water harvesting system was developed. The requirements of this system, among others, are: (1) to collect enough water for multiple use inside or outside the system, (2) to increase the desired production of the marginal saline land within the system, and (3) to provide an economically feasible long term farming system for the low-income community. Such a system is under development at the Ejido San Francisco del Barreal, near Parras in the State of Coahuila.

EXPERIMENTAL AREA OF THE WORKING MODEL

Mexican Ejido System and San Francisco Ejido

About one quarter of the 2.6 million people of the states of Coahuila and Chihuahua live in small rural communities or on rural holdings, and many of these are organized into ejidos.

An ejido is a group of farmers with the right to use an area of land. The farming land is usually worked as small individual units and the range is common, but all sorts of combinations can be found. An

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ejidatario is a member of an ejido. The ejidatarios are mainly involved in the subsistence cropping activities. They also exploit some desert plants, such as candelilla which produces a hard wax and ixtle which produces a fiber. The government is making a considerable effort to assist them to become self-sufficient in the short term and to produce marketable surpluses of fruit and other small industrial products in the long term.

The San Francisco Ejido is situated approximately 40 km south of Parra and is accessible only by a five to six hour trip over a rough road. The problems of this ejido are compounded by its inaccessibility which prevents daily access to the outside jobs and makes it important for the ejido to become self-sufficient.

The ejido has a total area of 2,400 ha with a population of 350 inhabitants, consisting of 79 ejidatarios. The main source of income is the sale of 1,000 Kg/month of candelilla for wax. There are 200 ha of dryland farming, 400 head of cattle, 300 goats, and 150 mules in the ejido.

Soils

Soils affected by salinity are found in the level lower-lying part of the ejido. They are underlaid by saline groundwater. The occurrence of this condition may be attributed to the extreme conditions of aridity and the lack of natural or artificial drainage facilities due to the flat terrain as well as the flat groundwater slope.

Analyses of soils in an abandoned dry farming area showed less salt and exchangeable sodium and indicated that it was more suitable for orchard development. The soil is slightly better in plant nutrients, contains up to 18% clay, and can be classified as a silt loam.

Rainfall and Water Supplies

The estimated elevation of this ejido is about 1,000 meters above mean sea level. The annual rainfall is between 200 and 250 mm. Most of the rainfall occurs during the period of April-July. Distribution of rainfall is very unpredictable. Although, no long term records are available near the site, it has been observed that 80% of the annual rain may fall in a few storms of short duration. This characteristic may be an advantage from the water harvesting point of view. For the purpose of designing the water system, annual rainfall was considered to be 250 mm.

There is a groundwater source about 3 m below the surface in the alluvial fill but it is saline. A domestic well drilled into an aquifer below the alluvium had better quality water but it was still relatively high in sodium (Table 1). The supply appears to be limited and should be used only in emergencies such as drought.

As shown in Table 1, the water in a surface reservoir (tank) adjacent to the ejido is of good quality. However, at the beginning of this project there was very little surface water available as most of the water collected was lost by surface evaporation, deep percolation, or inefficient application to crops.

Table 1: Chemical composition of tank and well waters

	EC x 10^3 mmhos/cm at 25° C	pH	Total soluble salts (ppm)	SAR	Cations (me/l)				Anions (me/l)					Class*
					Na	Ca	Mg	K	CO_3	HCO_3	Cl	SO_4	NO_3	
Open Tank Water	0.460	6.5	207	0.03	0.04	1.8	1.0	0	0.30	2.16	0.14	0.26	0	C_1 S_1
Saline Well Water	6.50	6.5	3021	9.41	28.52	11.30	7.10	0	0.20	3.75	27.32	16.7	0	C_4 S_3

*U. S. Salinity Laboratory.

DEVELOPING AND TESTING MULTIPURPOSE WATER SYSTEM

Compartmented Tank System

The shallow conventional tank normally cannot supply any water on a continuing basis. By dividing such a tank into two compartments, one deep and the other shallow, and using a pump to take water from the deep compartment, the carry-over efficiency can be increased to 25%. The use of the pump permits deepening of one part of the tank and reducing the surface area per unit of stored water.

At the start of the project, water was stored in a shallow tank covering over 2.5 ha; its maximum depth was only 1.5 meters. A second tank had a capacity of 8,600 m^3, with an average depth of 1.6 m. The latter was in a horseshoe shape, open at the upper end. This shape offered the possibility of easy modification by closing off the open end and excavating the bottom of the tank to increase the effective depth to 6 meters. This tank was utilized for the water harvesting agri-system described in the next section. Adjacent to this tank, a two compartmented tank was constructed, first using mules and then using a bulldozer (Fig. 3). Entrance of the water was restricted to one end while the other end was converted to a deep compartment. The deep compartment occupied 25% of the total area of 2,400 m^2, The collection compartment had an area of 1,800 m^2. With a depth of 2.5 m for a volume of 4,500 m^3. The reservoir area was treated with a sealant to control seepage.

The water quality was suitable for domestic use; people travelled long distances to collect water from these tanks for drinking and household use.

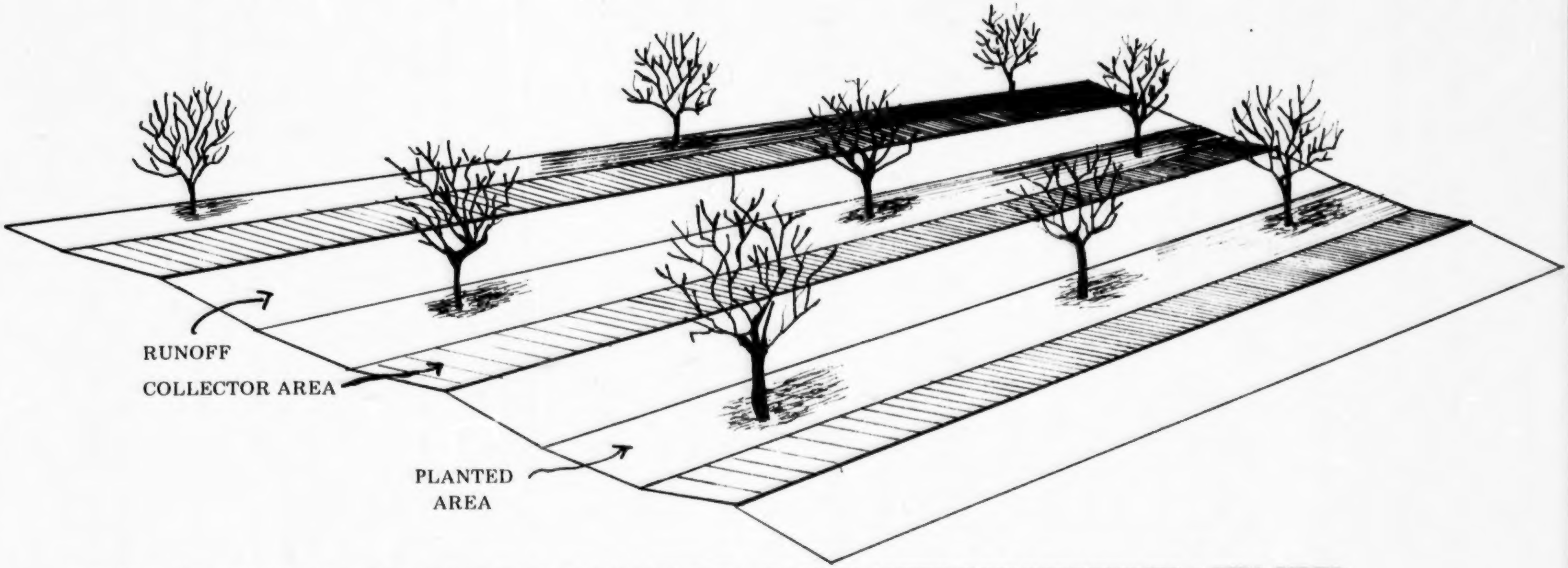
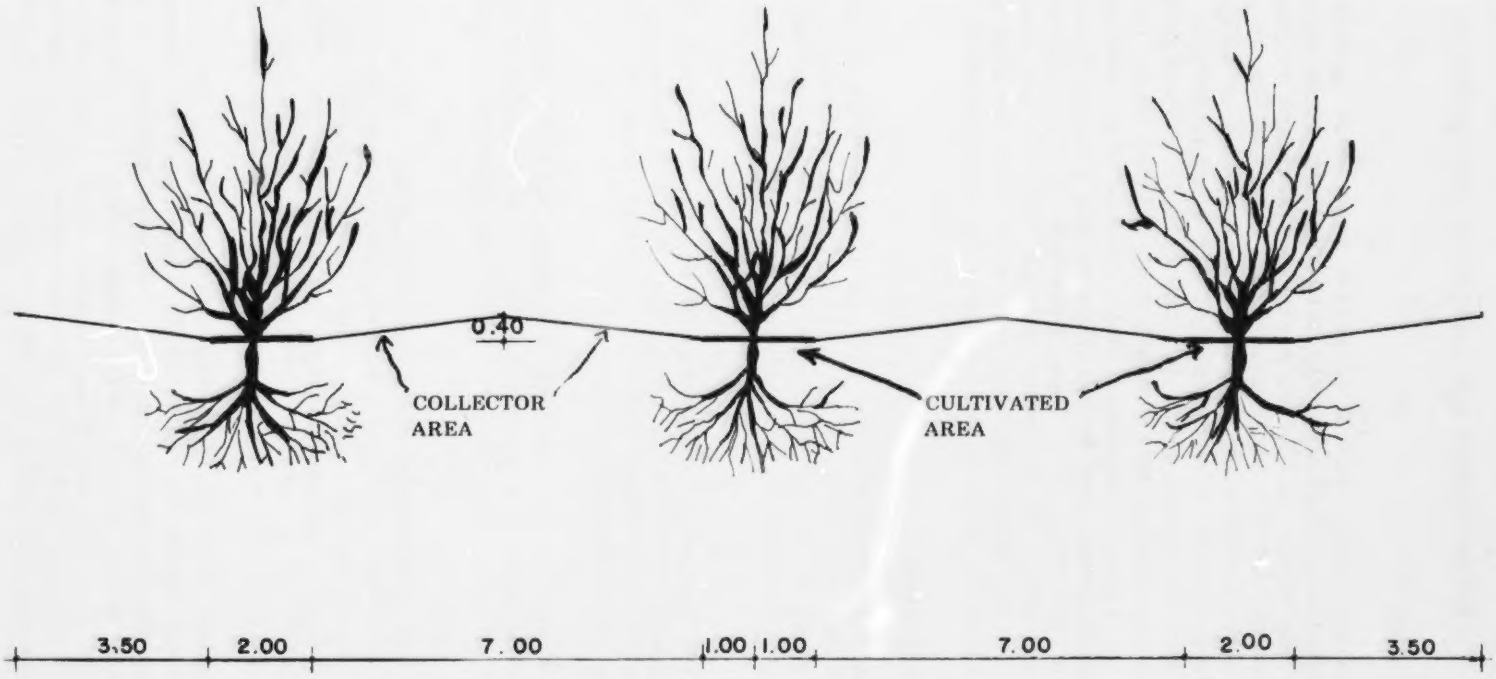

RUNOFF
COLLECTOR AREA
PLANTED
AREA

FIGURE 1: SHOWING DESERT STRIP FARMING SYSTEM. EACH PLANTED ROW REPRESENTS A TWO SIDED MICRO - WATERSHED

FIGURE: 2. TWO SIDED MICRO - WATERSHEDS


0.40
COLLECTOR AREA
CULTIVATED AREA
3.50
2.00
7.00
1.00
1.00
7.00
2.00
3.50

ESTABLISHMENT AND TESTING OF AGRI-SYSTEM

Land Preparation

A 20 ha area was first cleared of native vegetation (predominatly creosote and mesquite). Following the clearing, the 20 ha were laid out in strips 9 meters wide. A 2 meter strip in the center of the 9 meter strip was then root plowed for later planting. With the use of a small grader and manual labor, broad based terraces with ridges of 40 cms high at the center, were prepared on both sides of the 2 meter strip. The terrace served as water catchment areas for rainfall (micro-watersheads). The sides of the catchments were compacted by passing heavy roller drums over them after the first rainstorm. Then, 2 meter wide waterways (cultivated area) with a 2% grade were established on the 9 meter centers between each catchment terrace (Fig. 2). These waterways are used to conduct water from catchment areas to the water storage facility and also provide beds for planting. The broad base terraces with their cropped waterways in the center are referred to here as two sided micro-watersheds.

Planting Procedures

For best results crops selected for use in these beds should have relatively low water use, ability to survive moderate drought, deep roots to maximize the use of stored soil moisture, and high economic value. The crops selected for testing were pistachios, grapes, olives, almonds, beans and corn.

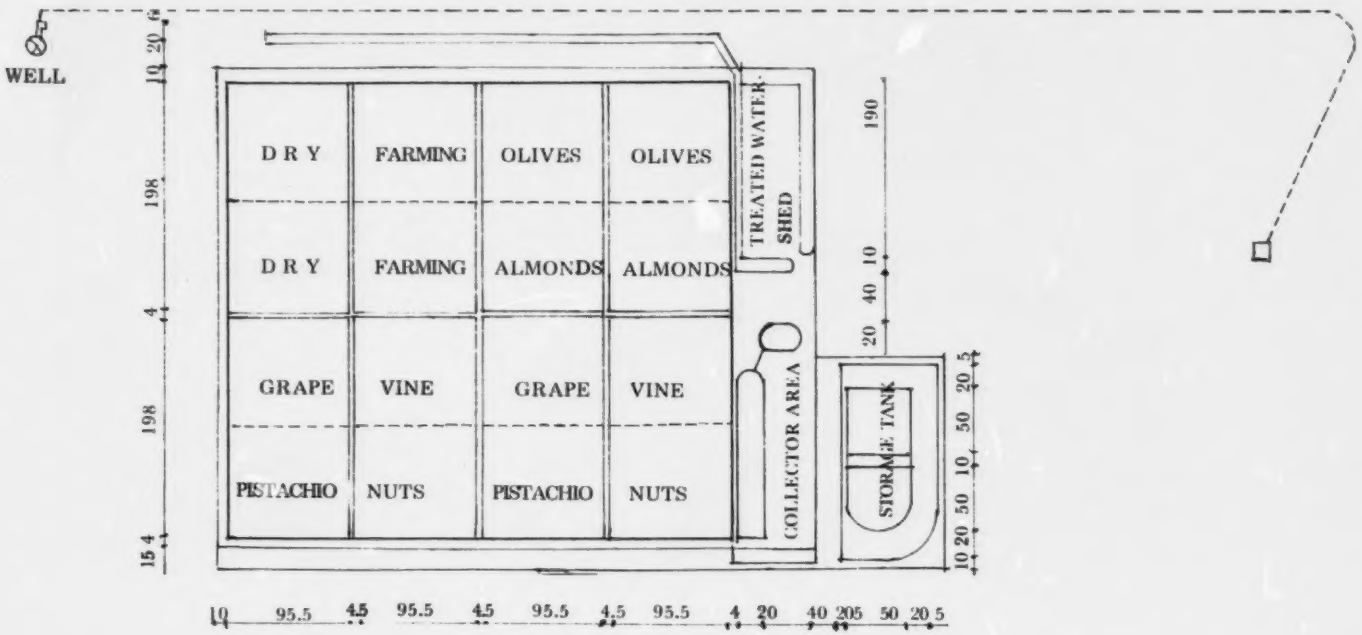
The pistachios and grapes were planted in plastic bags in the month of March, using well water for irrigation. Three saline water applications were made before sufficient rainfall occurred to provide water from the tank for the next two irrigations.

As shown in Figure 3, 15 hectares are being used for orchard development, with 5 hectares each of grapes and pistachios and 2.5 hectares each of olives and almonds. Five hectares are being cropped annually with corn and beans.

Fruit trees and grapes were placed in the center 2 meter strip. The planting was done as shown in Figure 2. Details of planting pistachios are described elsewhere (Nahlawi and Gavande, 1976). Trees within each row were spaced 4.5 m apart; grapevines were spaced 2 m apart. There are 22 rows of 27 trees each for a total of 594 trees per 2.5 ha section of land. There are 22 rows of grapevines at 120 per row for 2,640 grapevines.

The "dry farming" area was prepared the same way as the orchard area. Four rows of corn and beans were planted inside of each micro-watershed. Dry farming crops are to be planted only when soil moisture in the cultivated area and water stored in the surface tank reaches a prescribed level. It is anticipated that the area will be planted at least two out of three years, particularly when the orchard is growing and water irrigation demands are low. Supplemental irrigation probably will be needed in most years.

FIGURE: 3: INTEGRAL SYSTEM OF WATER STORAGE AND HARVESTING AT EJIDO SAN FEANCISCO DEL BARREAL.



WELL
DRY
FARMING
OLIVES
OLIVES
DRY
FARMING
ALMONDS
ALMONDS
GRAPE
VINE
GRAPE
VINE
PISTACHIO
NUTS
PISTACHIO
NUTS
TREATED WATER-SHED
COLLECTOR AREA
STORAGE TANK
10 20 6
198
4
198
15 4
190
10
40
20
20 5
50
10
50
10 20
10
95.5
4.5
95.5
4.5
95.5
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4
20
40
205
50
20 5

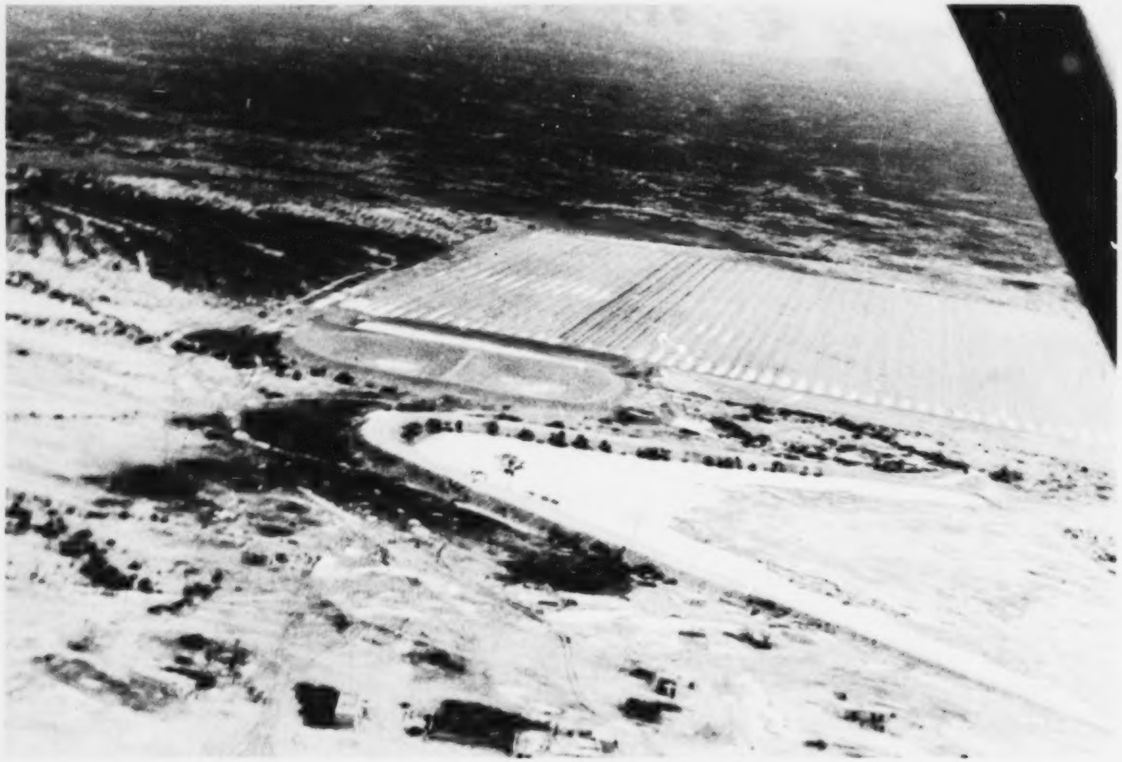

PLATE 1

Development of integral land use and water management system for fruit and crop production at San Francisco del Barrial Ejido, in Coahuila. Photo taken two months after orchard establishment and two days after the third rain storm.

Irrigation Treatments

Just after planting the pistachios and grapevines a field trial consisting of five treatments representing three salinity levels was established. The treatments were as follows:

1. Control diked waterway area where no irrigation water was applied and no run-off water was allowed to enter;
2. Four irrigations with saline well water. Each tree received about 40-50 liters per irrigation;
3. Two irrigations with saline well water alternated with 2 irrigations using tank water, at 40-50 liters/tree/irrigation;
4. Four irrigations with tank water, at 40-50 liters/tree/irrigation. Tank water was a run-off water from previous season.
5. Four irrigations with well water, at 40-50 liters/tree/irrigation. Same as treatment 2 above; however, additional run-off water from higher areas was directed toward the tree basins.

Each treatment consisted of two trees and was repeated in 2 or 3 random places within three micro-watersheds using randomized block design. Tree growth was carefully observed for each treatment. Three moderate size rainstorms occurred during the month of June, thus eliminating the need for further artificial irrigation. Following the rainstorms in June, soil samples representing each treatment were collected for analysis.

RESULTS AND DISCUSSION ON TESTING OF THE SYSTEM

The water harvesting system produced water of excellent quality (Table 1), allowing extra water for reclamation of saline soils. Once the total system described here starts functioning, the cost of operation and maintenance will be minimal.

Economic Analysis of the System

An economic analysis was made by FAO consultant Mactier (1975), by using the cost figures developed in this study and conservative estimates of both quantity and value of production. This analysis of 20 hectares of orchard and dry farming predicted a possible cash supply after year 4. The net benefit of the annual income in the year 10 per ejidatario will be (US) $7,116. In the year 20, it will increase to (US) $15,493 and level off at $19,683 per ejidatario, provided the number of ejidatarios remains at 79. This is a high income from 20 ha in this climatic area.

The operation appears to be sound, giving an internal rate of return greater than 25% and a benefit:cost ratio of 3:1 at a discount rate of 12% (Mactier, 1975).

Water Budget

The water budget estimation for the total system was obtained by using the data from an average year followed by the climatological data of 1956, 1957, and 1958. The years 1956 and 1957 had the lowest combined rainfall on record. The year 1958 had above average rainfall.

The amount of water stored in the tank was estimated at 15,000 m^3 (Cluff, 1976). With a consumptive use of 6,800 liters per year per tree for the orchard and 3,000 liters per grapevine the total consumptive use was estimated to be 15,000 m^3 per year when the orchard was fully grown. In the average year, the system ended up with approximately 1,000 m^3 more than it had at the start of the year (Cluff, 1976). There is expected to be ample water for the consumptive use of the orchard and also for supplemental water for the planted area of dry farming.

Establishment and Growth

Grapevines planted in the month of March have shown good growth; of the vines planted none have failed to survive. Thompson seedless variety was used (Plate 2).

Pistachio nut trees planted in early April also have shown reasonably good growth. The variety Pistachio atlantica was used as root stock. These root stocks were grafted in the month of June. Carmen (female) and Peters (male) scions were used for grafting, with a 10:1 distribution (female:male) in the field. Of the 75 trees planted, only one failed to survive. One seedling was found to be wilted shortly after planting, possibly due to a root cutting. Apparently, growth rate was not affected by different saline water treatments.

Soil Salinity and Sodium

Table 2 and 3 shows the effects of different levels of water application to grapevine and pistachio plots. Had there been no run-off water available for irrigation, salt distribution would have been similar to that of treatment B.

The tank water (D) was very effective in leaching the salts from the root zone for both crops. This treatment also caused the ESP to decrease markedly. The treatment of well water alternated with tank water appears to be reasonably effective in reducing salt and sodium accumulation.

In dry years, it is probable that the water harvesting system may not induce sufficient run-off towards the tree basin and towards the water storage facility. Under these conditions saline well water may be used as an emergency measure. This indicates the possibility of using well water mixed with tank water, or alternately, with the tank water, alone, as a source of supplementary irrigation.

As indicated before, soils in the plots were moderately permeable and, as

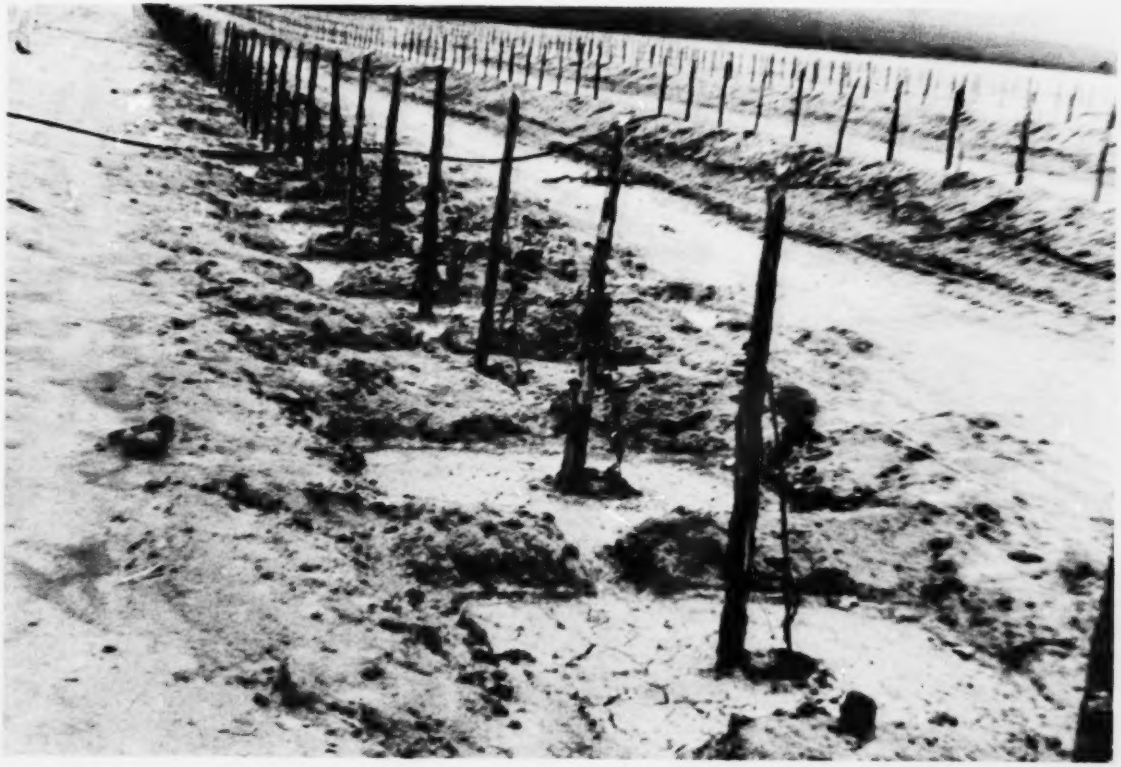

PLATE 2

Planting of one-year old grapevine in two sided micro-watershed system. Photo taken two months after planting and just two days after third rain storm.

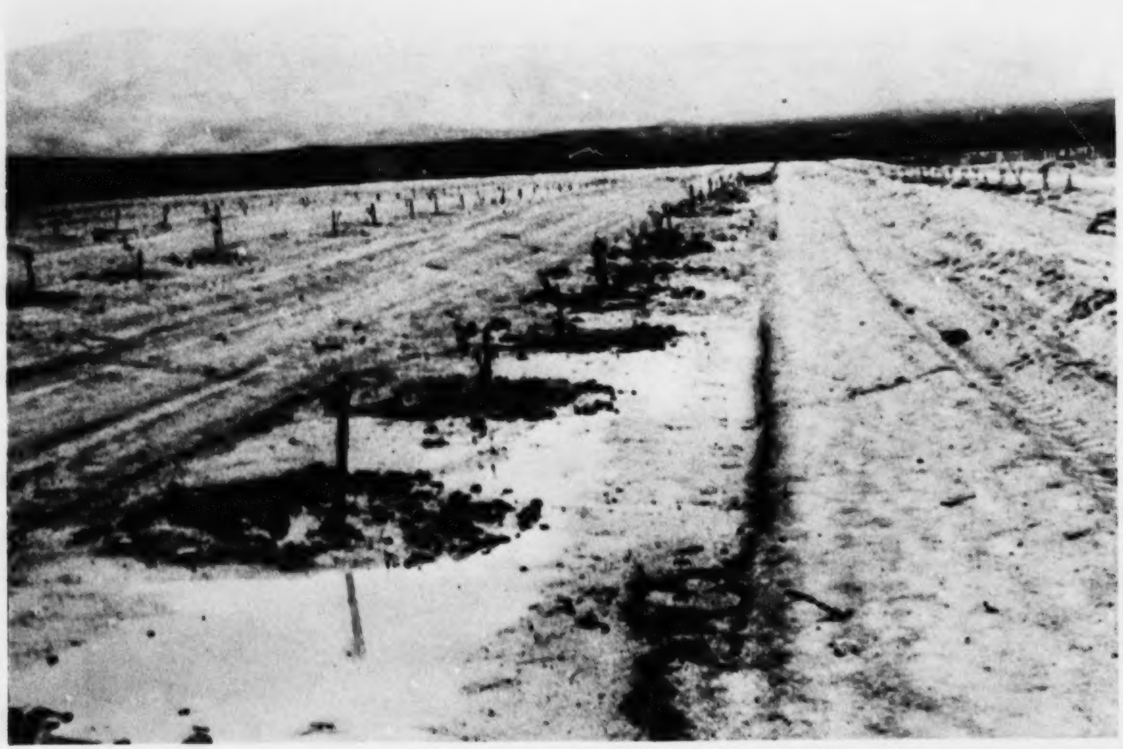

PLATE 3

Planting at one year old pistachios in two sided micro-watershed system. Photo taken two months after planting and two days after third rain storm.

Table 2 - EFFECT OF IRRIGATION TREATMENT ON CHEMICAL COMPOSITION OF SOIL IN GRAPEVINE PLOTS.

Irrigation Treatments	Soil Depth	$ECx10^3$	pH	Soluble				S A R	E S P	Saturation (%)
				Ca ppm	Mg ppm	K ppm	Na ppm			
A Control (Untreated plots)	0-30	2.4	8.2	1200	82	70	520	17.1	19.1	47.6
	30-60	2.9	8.2	880	82	27	2281	31.1	31.0	38
	60-90	8.9	7.8	5660	43	35	2120	11.5	13.5	40
	90-120	10.8	8.1	3990	497	70	1800	11.3	13.5	47.6
B Saline Well Water	0-30	.4	8.3	897	65	25	880	12	14.0	45
	30-60	1.4	8.2	1520	82	30	2204	23.9	25.0	40
	60-90	12.3	7.7	9860	732	87	2153	8.8	10.8	49
	90-120	11.4	7.5	6397	665	87	1560	10.8	9.8	44
C Well + Tank Water	0-30	0.5	7.9	832	130	162	20	.25	.2	46
	30-60	0.6	8.1	832	130	75	48	.62	.2	46.8
	60-90	0.7	8.3	577	65	50	600	10.0	10.0	32.8
	90-120	1.0	8.3	897	65	50	560	7.7	9.7	38
D Tank Water	0-30	.4	8.1	897	65	138	48	.64	.2	42.8
	30-60	.5	8.0	897	65	65	104	1.2	1.1	38
	60-90	1.0	8.3	610	32	82	40	.68	.80	32
	90-120	.5	8.3	910	50	55	240	3.3	3.3	34
E Well Water + Run Off	0-30	.6	8.0	850	120	110	80	1.0	0.5	43
	30-60	.53	8.15	1030	125	70	25	.95	0.66	42
	60-90	.33	8.05	700	73	40	10	.13	0.20	43
	90-120	.33	8.15	755	65	6	22	.33	0.20	41

Table 3 - EFFECT OF IRRIGATION TREATMENT ON CHEMICAL CHARACTERISTICS OF SOIL IN PISTACHIO PLOTS

Irrigation Treatments	Soil Depths	$ECx10^3$	pH	Soluble				SAR	ESP	Saturation (%)
				Ca ppm	Mg ppm	K ppm	Na ppm			
[A]Control (Untreated plots)	0.30	3.8	8.2	2300	265	35	2204	18.3	20.3	50
	30-60	10.8	7.9	5890	530	70	2153	11.3	15.3	48
	60-90	11.4	7.9	3350	490	80	2409	16.2	18.2	40.8
	90-120	11.5	8.0	2420	465	80	2205	16.9	18.2	40
[B]Saline Well Water	0-30	4.6	8.1	1727	197	1.2	2180	21.0	20.9	48
	30-60	6.0	8.0	2237	330	30	2330	19.0	21.2	41.2
	60-90	7.0	9.8	2270	297	50	2330	19.0	21.0	46
	90-120	8.4	7.7	4060	432	37	2360	14.8	16.8	38
[C]Well + Tank Water	0-30	0.4	7.9	562	80	155	20	0.3	0.2	43.6
	30-60	0.4	7.9	562	80	90	20	0.3	0.2	48
	60-90	0.25	8.0	577	65	55	20	0.3	0.25	48.8
	90-120	0.30	8.0	562	80	90	20	0.3	0.25	48.8
[D]Tank Water	0-30	0.5	8.3	882	80	82	20	0.2	0.4	47.6
	30-60	0.3	7.7	897	65	6	20	0.2	0.25	48
	60-90	0.4	8.2	897	65	105	20	0.2	0.3	42.8
	90-120	0.3	8.1	897	47	50	40	0.56	0.45	40
[E]Well Water + Run-off	0-30	0.36	8.3	700	135	110	40	.45	0.2	54
	30-60	0.46	8.1	610	110	140	53	.50	0.2	45
	60-90	0.30	8.1	550	80	60	46	.80	0.8	44
	90-120	0.36	8.2	580	80	80	40	.55	0.6	40

expected, drainage was reasonably good. This helped to leach the salts rapidly. However, once the loose layer in the catchment and cultivated area settles down, the permeability in the cultivated area is likely to be lowered and the leaching rate may be reduced. Experience in other areas shows that the efficiency of a micro-watershed system increases after the second year or third year of its construction.

CONCLUSIONS

Adoption of compacted micro-watersheds has, thus far, helped to collect enough good quality water for fruit and crop production, as well as for domestic use. Use of this practice also helped to make possible the use of saline well water for irrigation in an area with marginal saline soils.

Establishment of an orchard together with dry farming, using the most adequate species of fruit trees and crops, seems to satisfy both long term and short term needs of the low income community.

LITERATURE CITED

Cluff, C. B. 1976. Consultant report in Hydrology. FAO/UNDP Project Mex/74/003. FAO, Rome, Italy.

Mactier, L. A. W. 1975. Consultant report in agricultural economics and farm management. FAO/UNDP Project Mex/74/003. G. P. McGowan & Associates Pty. Ltd. Albury, NSW, Australia.

Nahlawi, N. and S. A. Gavande. 1976. Establishment of pistachios in arid zones of Mexico. Special technical bulletin, FAO/UNDP, Mex/74/003. FAO, Rome, Italy (in press).

COMPOSITION OF SALINE DRAINAGE WATER IN IRAQ AND ITS USE

Augustine B. Hanna[1]

INTRODUCTION

This study is aimed to determine the composition of dissolved salts in main drains and collectors in Iraq, to study the seasonal fluctuations of the salt concentration and its composition, and also the possibility of using these waters for the first stages of leaching saline and saline-alkali soils.

About 25 billion cubic meters of drainage water are annually discharged to the sea, rivers, and depressions. Any use of this large amount of water, which represents one third of the total amount of water brought to the country by both the Tigris and Euphrates rivers, would be of great economic value.

MATERIALS AND METHODS

Monthly water samples were collected for this study between January, 1973 and June, 1975 from fifty sites covering the most important main drains and collectors.

For leaching experiments, surface soil samples from the Abu-Ghraib area were used and several columns were made for this purpose. The length of these columns was almost the same as the depth of the soil in the field, i.e., 30 cm.

Drainage water used for this experiment was taken from Saglawiya drainage canal which is adjacent to the soil sample site. Irrigation water from the same vicinity was used for leaching in order to compare it with the drainage water.

The methods used for analysis of water and soil samples were according to U. S. Salinity Laboratory, Handbook No. 60 (1954).

RESULTS AND DISCUSSION

Drainage water

Electrical conductivity of the drainage water (Table 1) varies from about 7 to 52 mmhos/cm. The SAR ratio, however, increases as the concentration of salts increases indicating that the dominant sodium salts in the saline-alkali soils are easily leached out. This ratio is about 5 in low saline waters and 36 in other high saline waters. The same trend is also noticed in the soils of the middle and southern part of Iraq (Buehrer and Hanna, 1955). In the Tigris and Euphrates rivers this

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[1] State Organization of Soils and Land Reclamation, Baghdad, Iraq.

Table 1: Chemical Composition of Drainage Water

			Mole Equivalent Ratio							me/1		
Location	EC mmhos/cm	pH	Ca: Mg	Ca: SO_4	SAR	Na: Cl	SO_4: Cl	SO_4: Anions	Cl: Anions	K	HCO_3	CO_3
Ishaqi (West Drain)	8.3	8.3	0.26	0.24	8.2	0.87	1.10	0.51	0.47	0.22	2.3	-
Khalis (Diyala)	7.7	8.2	0.46	0.19	11.1	1.46	1.68	0.59	0.35	0.20	3.3	0.54
Diyala (Main Drain)	8.2	8.5	0.31	0.19	10.2	1.36	1.47	0.55	0.37	0.31	5.8	0.95
Hawija (West Drain)	11.5	8.2	0.32	0.25	16.4	0.99	0.63	0.38	0.60	0.40	2.1	-
Habaniya	16.5	8.3	0.36	0.22	16.1	1.00	0.92	0.47	0.51	0.47	2.2	1.60
Karbala (Razaza)	8.2	7.9	0.52	0.23	10.0	1.20	1.40	0.57	0.40	1.60	1.3	1.30
Hilla-Kifel	30.0	8.3	0.17	0.16	26.8	0.95	0.51	0.33	0.65	1.90	4.9	0.70
Dujaila	52.2	7.7	0.33	0.32	36.3	0.78	0.32	0.24	0.75	0.66	2.4	-
Basra (Tanuma)	30.3	7.9	0.29	0.23	31.2	1.60	0.70	0.40	0.58	1.20	2.2	-
Basra (Suwaib)	32.0	8.0	0.34	0.25	33.2	0.84	0.38	0.27	0.72	1.90	2.5	-

Table 2: Seasonal Fluctuations of Chemical Composition of Drainage Water

				Mole Equivalent Ratio							me/1		
Location	Time of Sampling	EC mmhos/cm	pH	Ca: Mg	Ca: SO_4	SAR	Na: Cl	SO_4: Cl	SO_4: Anions	Cl: Anions	K	HCO_3	CO_3
Imara (Sugar Cane Drain)	May, 1973	7.2	8.0	0.27	0.07	13.0	0.91	0.85	0.44	0.52	0.46	4.0	-
Imara (Sugar Cane Drain)	July, 1974	14.1	8.0	0.29	0.09	16.3	0.93	1.36	0.56	0.42	0.84	2.9	-
Saglawiya	May, 1973	13.4	8.2	0.38	0.24	19.3	1.20	0.81	0.45	0.52	-	5.3	-
Saglawiya	July, 1974	19.2	8.0	0.25	0.18	21.0	1.10	0.79	0.43	0.54	0.47	4.5	0.7
Mussaib (North Drain)	May, 1973	17.8	7.9	0.31	0.30	16.0	0.84	0.54	0.34	0.63	0.60	4.3	-
Mussaib (North Drain)	July, 1974	28.0	8.2	0.31	0.60	19.1	0.95	0.37	0.27	0.71	0.47	2.8	1.9
Mussaib (South Drain)	May, 1973	18.9	7.9	0.24	0.29	17.0	0.76	0.39	0.27	0.71	0.38	2.6	0.8
Mussaib (South Drain)	July, 1974	32.0	8.1	0.22	0.17	30.0	1.10	0.62	0.37	0.59	1.20	8.1	1.8

ratio is almost a function of total soluble salts (Hanna and Al-Talabany, 1970).

Calcium-to-magnesium equivalent mole ratio rarely exceeds unity. It varied from 0.1 to 0.5. This could be due to exchange reactions and precipitation of calcium as calcium carbonate (Table 5) and possibly to some extent as gypsum in soils. Generally this ratio decreases with increasing salinity of drainage water (Table 1). In most soils of Iraq this ratio is relatively opposite that of the drainage water, soil calcium is more abundant than magnesium. This is also true for most surface water in Iraq (U.S. Salinity Laboratory Staff, 1954; and Hanna and Al-Talabany, 1970).

Calcium-to-sulphate equivalent ratio (Table 1 and 2) in all drainage water varies from 0.1 to 0.6. This could be attributed to removal of calcium from the system as was mentioned previously. This ratio in river water is always more than one and even two in some places. In saline soils, however, this ratio exceeds one; it is less than one in most saline-alkali soils.

Sodium-to-chloride equivalent ratio varies from 0.7 to 1.5 and generally the higher the salt content in the water the greater is this ratio, as is the case for surface water and most of the saline-alkali soils in the country.

Sulphate-to-chloride ratio (Tables 1 and 2) varies from 0.3 in highly saline water to almost 2 in less saline drainage water. This ratio in the Tigris water is always higher than one, whereas in the Euphrates water, it is always lower than one. Projects that are irrigated from the Euphrates, like Habaniya, Saglawiya, and Hilla-Kifel, have generally a SO_4:Cl ratio less than one; while in Khalis, Diyala, Ishaqui, and Imara, which are irrigated from the Tigris, this ratio is more than one (Tables 1 and 2).

Sulphate-to-total-anions ratio increases as total salts decrease. It varies from 0.2 in high saline water to about 0.6 in less saline water. The chloride:anion ratio is directly correlated with total soluble salts. In all cases the sum of chloride and sulfate in the drainage water is more than 90 percent of the total anions, contrary to the irrigation water, in which this sum does not exceed 70 percent of the total anions.

Carbonate is present in most drainage water. It varies from 0.5 to 1.6 me/l. Bicarbonates varied from 1.3 and 5.8 me/l.

The monthly fluctuation of salinity is great in all drains. It appears (Table 2) that the lowest salinity in most drains occurs during the flood period, especially in May. This fluctuation in total salinity is more pronounced than the composition of the salts. In Imara (Sugar Cane Drains) the electrical conductivity of the drainage water in May, 1973 was 7 mmhos/cm and in July, 1974 it almost doubled.

Little variation is noticed in the ion ratios between the two samples.

The same observation is true for Mussaib (North) drain and Saglawiya main drain, while in the Mussaib (South) drain there is a greater variation in the two ratios.

First Leaching Experiment

The leaching experiment showed (Table 3A) that the first leachate has a conductivity of 450 mmhos/cm, which is 45 times greater than the salinity of the drain water used for leaching. The SAR ratio of the leachate increased to 21.1, indicating that the rate of extraction of sodium salts is within the ratio of their presence in the soil prior to leaching (Table 5). Carbonates, however, disappeared in this leachate due to the precipitation of calcium as calcium carbonate (Hardan, 1971).

The conductivity of the second leachate (Table 3A) decreased drastically to 14.5 and the SAR ratio to 9.6, which is close to the ratio of the drain water. The calcium-to-magnesium ratio however is nearly one, indicating that the calcium reserve in the soil is not yet depleted.

The ratio of sulphate to chloride increased from 0.01 to 1.28, showing that chlorides were almost removed in the first leaching. Potassium, however, decreased in the second leaching, indicating the end of the soluble phase and the beginning of the exchangeable and fixed forms.

The third and fourth leachates had a salinity near to that of the drain water and the SAR ratio was lower than that of the drain water, indicating the presence of a reserve of calcium in the soil, most probably as gypsum. This is indicated in the increase in the sulphate to chloride mole ratio and the amount of gypsum present in the soil after leaching (Table 5).

Leaching the soil with irrigation water after the drain water leaching lowered the salinity and the SAR ratio very slowly. After five successive leachings the salinity became 4.6 mmhos/cm and the SAR ratio 2 (Table 3B).

Second Leaching Experiment

In the second experiment the soil was leached with irrigation water, (Table 4) with and without a pre-washing with drain water. The composition of the first leachate is very similar to the first leachate using drain water. In the second leachate the salinity decreased to 7.1 mmhos/cm and the SAR ratio to 4.9. Changes in the latter leachates are very slow and resemble those in the previous experiment.

Analyzing the soil samples after leaching indicated almost similar composition whether irrigation water, alone, was used or drain water plus irrigation water (Table 5). The total amount of the irrigation water used in the first and second experiments was 500 and 690 ml, respectively.

Table 3A: Composition of leachate following leaching with drain water

Leachate No.	Volume ml	Conductivity, mmhos/cm	SAR	me/1									ppm
				Ca	Mg	Na	K	Cl	SO_4	HCO_3	CO_3	NO_3	PO_4
1	156	450.0	21.4	1460	1620	820	8.7	3690	49	2.4	Nil	3.3	2.9
2	100	14.5	9.6	48	52	68	1.2	74	95	3.6	Nil	-	-
3	100	12.0	7.2	40	62	51	1.1	48	90	6.8	Nil	0.1	1.2
4	100	11.0	7.6	42	50	51	1.1	48	81	6.4	0.8	0.1	2.7
Water	-	10.0	10.1	14	46	55	0.4	48	83	6.4	0.8	0.1	4.7

Table 3B: Composition of leachate following leaching with irrigation water

Leachate No.	Volume ml	Conductivity, mmhos/cm	SAR	me/1									ppm
				Ca	Mg	Na	K	Cl	SO_4	HCO_3	CO_3	NO_3	PO_4
1	100	11.0	7.9	38.0	46.0	51.5	1.00	45.0	82.0	7.2	0.4	Nil	4.1
2	100	8.5	7.9	30.0	46.0	49.5	1.00	30.0	96.0	8.8	-	Nil	3.8
3	100	8.0	6.7	26.0	32.0	36.8	0.90	9.0	75.0	6.4	0.2	Nil	3.5
4	100	5.0	3.8	34.0	24.0	20.5	0.80	6.0	73.0	6.8	Nil	Nil	3.5
5	100	4.6	2.1	28.0	30.0	11.2	0.70	4.5	60.0	7.2	Nil	Nil	3.8
Irrigation Water	-	0.8	1.1	3.2	3.2	1.9	0.02	2.1	3.0	3.2	Nil	Nil	-

Table 5: Chemical composition of soil before and after leaching

Treatment	ECe mmhos/cm 25°	me/1								SAR	% Gypsum	% Lime	CEC me/100g	ESP	Ext. K me/100g	% OM	ppm PO_4
		Ca	Mg	Na	K	Cl	SO_4	HCO_3	NO_3								
Leached with drain water	7.0	24.3	27.8	28.3	0.7	24.0	59.8	3.6	-	5.6	0.5	20.2	22.6	8.4	1.0	1.3	6.4
Leached with drain water and irrigation water	3.1	21.1	15.3	5.4	0.5	1.3	41.7	2.4	-	1.3	0.2	20.0	22.0	1.4	0.9	1.4	9.5
Leached with irrigation water	2.1	22.7	12.3	2.2	0.5	1.7	32.4	2.3	-	0.5	0.2	19.8	22.2	1.4	0.9	1.3	8.6
Untreated soil	124.0	487.0	576.0	457.0	2.9	1448.0	18.6	1.5	12.4	20.0	0.5	18.8	21.2	35.1	1.0	1.7	8.2

Table 4: Composition of leachate following leaching with irrigation water

Leachate No.	Volume ml	Conductivity mmhos/cm	SAR	me/1									ppm
				Ca	Mg	Na	K	Cl	SO_4	HCO_3	CO_3	NO_3	PO_4
1	156	425.0	20.2	1460	1700	802.0	8.3	3870	35	2.4	Nil	3.2	4.7
2	100	7.1	4.9	28	38	28.5	0.9	18	79	2.8	Nil	0.2	3.8
3	100	5.3	1.8	30	30	10.1	0.9	9	59	3.2	Nil	Nil	4.1
4	100	4.4	0.7	30	28	3.7	0.9	9	55	4.8	Nil	Nil	5.4
5	100	4.0	0.5	28	34	2.5	0.8	9	55	4.0	Nil	Nil	3.9

CONCLUSIONS

This study showed that leaching with drain watere having an EC of 10 mmhos/cm, followed by leaching with irrigation water, was as effective as leaching with irrigation water only. It is apparent that drain water can be used in the first stage of leaching saline soils. Final leaching to reduce soil salinity can then be done with good quality irrigation water.

LITERATURE CITED

Buehrer, T. F., and Augustine B. Hanna. 1955. The nature of the saline (sabakh) soils of Iraq and their desalination. Trans. Int. Cong. Soil Sci., Paris A:266.

U. S. Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soil. USDA Handbook No. 60.

Hanna, Augustine B., and K. Al-Talabany. 1970. Quality of the irrigation water of Iraq. Seminar on Saline and Waterlogged Soils. FAO, UNDP. Baghdad, Iraq. pp. 1-4.

Hardan, Adnan. 1971. Removal of salts from undisturbed saline-alkali soil columns by different leaching waters. Iraqi Journal of Agricultural Science. pp. 409-431.

MAP OF SALTY SOILS OF AFRICA

G. Aubert [1]

INTRODUCTION

The map of salty soils of Africa was prepared as part of a joint project of the Subcommission on Salt-Affected Soils of the 5th Commission (morphology, genesis, and classification of soils) of the International Society of Soil Science and the Division of Natural Resources of the Department of Sciences of UNESCO to prepare saline soils maps of the continents.

As part of that project, two reports have been published: Australian Soils with Saline and Sodic Properties by K. H. Northcote and J. K. M. Skene (1972) with a map at the scale of 1 to 5 million, and Salt Affected Soils in Europe by I. Szabolcs (1974) with two maps, one at a scale of 1 to 5 million for the entire continent and the other at a scale of 1 to 500,000 for Hungary.

The draft map presented at the International Salinity Conference will be revised and published after a meeting of African soils scientists in 1977. The scale will be 1 to 5 million, the same as the draft map. In conformity with United Nations directives, Libya, Egypt, and the Sudan are included in the Near and Middle East map prepared by M. M. Elgabaly rather than in the map of Africa.

PROCEDURE

We have utilized the two 1 to 5 million soils maps of Africa prepared by J. d'Hoore (1964) and FAO/UNESCO (1975), as well as numerous maps published at that scale or at a larger scale for various African countries. Additionally, several reports and documents of the United Kingdom Land Resources Division and O.R.S.T.O.M. have been used. The assistance provided by S. A. Radwanski and G. Murdoch of the Land Resources Division and by J. Boyer and A. Mori of O.R.S.T.O.M. has been particularly helpful.

First drafts of the Africa map were presented at Subcommission meetings in Yerevan in 1969 and Cairo in 1972. A map of the savannah region was prepared for the meeting of the 4th, 5th, and 6th Commissions of the International Society of Soil Science at Tema-Accra in 1975.

Since the beginning of 1976, draft maps have been sent to the chiefs of soil services in several countries of Africa for verification of the accuracy of the delineations. Changes recommended by the reviewers have been incorporated into the present map, which represents the combined efforts of numerous colleagues.

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CARTOGRAPHIC UNITS

Cartographic units used on the map have been defined at previous meetings of the Subcommission on Salt Affected Soils. The units are:

A. Saline and Alkali Soils

1. Saline soils and solonchaks
2. Alkali soils, including solonetz and solodized soils

B. Other Cartographic Categories Shown

1. Percent distribution of salt affected soils within delineations
2. Salt affected soils of lunettes
3. Salt affected mangrove soils
4. Potentially salt affected soils
    a. Associated with presently salt affected soils
    b. Not associated with presently salt affected soils

ORIGIN OF SALT AFFECTED SOILS OF AFRICA

Soils affected by soluble salts or by their ions occupy immense areas in Africa: more than 650,000 Km^2 according to the FAO/UNESCO map, and much more according to the present map. The differences are due to the differences in definitions. Salt affected soils are especially prevalent in northern Africa, South Africa, and Botswana, and are common in the arid or semiarid zones of tropical Africa (Senegal, Mauritania, Upper Volta, Chad, northern Cameron, Swaziland, Malawi, Kenya, Zambia, Rhodesia, southern Angola, and southern Mozambique). Only Zaire, Congo, the Central African Republic, Gabon, Ivory Coast, and Liberia are virtually free of such soils.

The affected soils are very diverse in characteristics and in origin. The salts responsible for the formation of salt affected soils, as is perhaps usual in a large continent, are of marine or continental origin or are carried to the surface in artesian waters.

Salt Affected Soils Caused by Salts of Marine Origin

1. Existing Seas

It is possible that certain zones of saline soils of Africa owe their existence to tidal waters. To our knowledge, they have not however been described or mapped. If they exist, they certainly are of little extent. On the other hand, in numerous regions with alternating wet and dry periods, the sea extends far inland - sometimes more than 100 km - in the estuaries and deltas and their tributaries. Its effect is to cover the land with salty water, which persists until floods during the rainy season push some of the salty water back toward the sea. The salts gradually move through the soils and enter the ground water system. One of the typical examples of this is the pseudo-delta of Senegal. Others can be found in Madagascar, Tanzania, and Southwest Africa.

Over a large area, sea water is in contact more or less directly with the ground water of the litoral zone. In many arid and semi-arid coastal regions, and sometimes in humid areas, the process of evaporation brings saline ground water to the surface by capillary movement from shallow water tables, leading to strong soil salinization (Algeria, Morocco, Senegal, Sierra Leone, Togo, Ghana, and southern Madagascar).

In humid tropical regions, the coastal saline soils of estuaries and deltas which are rich in organic matter acquire special characteristics where the mangroves are associated with _Avicennia_ or _Rhizophora_ vegetation. Where such soils are drained, they become extremely acidic. They are classified as Thionic Fluvisols and have been studied in Sierra Leone, southern Senegal, the Gambia, Guinea Bissan, Guinea, Liberia, Nigeria, Cameron, Gabon, Kenya, Tanzania, Mozambique, and in western Madagascar.

Saline soils owing their origin to present-day marine influences usually are very saline (solonchaks) and have decreasing salinity with depth. They may show a weakly developed salt crust or a horizon of pseudo-sand (very fine aggregate of saline-alkali clay) on the surface. In more humid regions, salinity may increase with depth, but this is relatively rare.

2. Extinct Seas

Soils affected by salts deposited from former seas during the Quaternary period are widespread in Africa. Saline parent material has given rise to saline soils wherever the climate is favorable for salt accumulation. This is the case in the lower valley of the Chelif River in Algeria, in the pseudo-delta and the valley of the Senegal River, in Southwest Africa, and in numerous other countries.

Moreover, some gulfs have become filled, little by little over the last 3,000 to 4,000, by the alluvial and colluvial deposits. The sea water thus trapped gives rise to saline lakes and, finally, to saline ground water which often is close to the soil surface, such as in the lower valley of the Medjerda River in Tunisia. As before, the dominant ions are chloride, sulfate, and sodium.

3. Transported Marine Salts

Transported marine salts constitute another source of soil salinity in certain parts of Africa. In several cases, the principal salt deposited as the result of leaching of ancient marine rocks is gypsum; others include sodium and magnesium sulfate and chlorides. Rocks of Triassic and Miocene age in northern Africa and Triassic or Permian in Rhodesia and South Africa are important sources of soluble salts and gypsum.

While ancient rocks may be covered with saline soils, their more significant effect on salinity is felt in depressions or in lower parts of valley systems into which runoff water drains. Salts brought to the surface by evaporation during dry periods are deposited and accumulate at lower levels when floods sweep across the drainageways.

Utilization of saline ground water from these geologic materials for irrigation is another source of salt affected soils when drainage is poor and the climate is arid. Even when the rainfall is as much as 1,000 mm, low lying impermeable soils may be saline if annual evaporation is high, as it commonly is in tropical Africa. Transported marine salts are often the source of soil salts in Morocco, Algeria, Tunisia, northern Nigeria, Swaziland, Botswana, and South Africa.

Accumulation of soluble salts can be the result of a pedogenetic process involving seepage of rain water. Salts have been shown to accumulate beneath calcrete horizons in Morocco and Algeria. Breaking up or removal of calcrete to permit cultivation of land risks the possibility that the underlying salts will then rise to the soil surface.

Commonly, the soils affected by transported marine salts are solonchaks with a cation exchange complex dominated by calcium and magnesium or by sodium. There sometimes is a more or less thick salt crust or a pseudo-sand horizon of five to six centimeters in thickness on the surface. That is the case in Algeria, Southwest Africa, and South Africa. Alkali soils having a similar origin occur in Morocco, Algeria, and northern Nigeria. Solonetz soils have been noted in Botswana where rainfall is greater.

The soil salts generally are largely chlorides but sulfates often are of great local importance, as in the formation of gypsiferous soils. The dominant cation normally is sodium but it may be the calcium-magnesium combination. Hydroscopic soils composed principally of calcium and magnesium chlorides have been observed in the Hauts Plateaux of Algeria, where they are weakly alkaline, and in the Sabi Valley of Rhodesia, where they are acidic.

In zones where the salt affected soils have a marine salt origin, their extension, whether natural or due to irrigation or other management practices, is growing. The spread of salt affected soils is gradually outward from a source or is of a spotly nature.

Salt Affected Soils Caused by Salts of Continental Origin

Weathering of rocks containing sodium minerals (feldspars, amphiboles, etc.) produces soluble sodium salts, principally carbonates and bicarbonates, often sulfates, sometimes silicates, and rarely chlorides. Such rocks are numerous and often of great extent in Africa. Under certain conditions of climate and topography, their weathering products may accumulate and lead to the formation of saline or sodic soils.

In arid regions, closed basins such as Lake Chad are practically always saline due to the salts brought in by streams draining into the basins. The principal salt affected soils are solonchaks, frequently with salt crusts on the surface or strongly saline horizons at shallow depths, as in Chad, Kenya, Botswana, and Mali, among others. Many of the salt crusts containing concentrated sodium carbonate or sodium chloride are exploited commercially. In marshy areas where the soils are rich in organic matter, as in certain branches of Lake Chad, a variety of salt affected soils may be formed (Cheverry, 1974).

In subhumid regions and in certain semiarid regions where excess water accumulates, the situation is different. Here, the dissolved sodium accumulates as exchangeable sodium in the B horizon, due to vertical or horizontal leaching. The soils which result are solonetz, solodized soils, or solodized planosols. Formation of these solodized soils is favored by hydromorphic conditions and high soil temperature. They are found in Upper Volta, northern Togo, northern Nigeria, northern Cameroon, Chad, Malawi, Botswana, Rhodesia, Swaziland, Lesotho, and other tropical countries. Solonetz and solodized soils are very susceptible to water erosion. They are generally associated with higher lying Leached Tropical Ferruginous Soils (Chromic or Ferralitic Luvisols),which often are hydromorphic, and lower lying vertisols (Bocquier, 1971).

Numerous vertisols have a B horizon with a very high exchangeable sodium percentage and possess the physical properties of alkali soils. They occur in Tunisia, Kenya, Tanzania, Uganda, Zambia, Lesotho, Swaziland, and South Africa and have been classified as alkali soils.

Salt Affected Soils Caused by Saline Artesian Waters

Salts in artesian waters originate either from saline sediments or by alteration of native rocks. Most of the waters are moderately or slightly saline; they become concentrated by evaporation in soil strata at or near the surface. The chotts of Algeria and Tunisia (Belkhodja, 1972). are examples of vast areas where salt crusts have formed as the result of artesian waters rising to the surface.

Salt affected soils of Africa are quite variable in their characteristics and origin. Some of them are unlikely to increase in area, others are likely to do so. Salinization is a threat in many places where salinity is not presently a problem, which makes it important to study the process of salinization and to maintain continued surveillance of susceptible areas. The FAO/United Nations Environment Program on soil degradation and desertification, with the collaboration of Unesco and other national and international organizations, can be the source of very valuable information on soils and land management throughout the world. It needs continued support.

SUMMARY

A draft map of the distribution of salt-affected soils of Africa has been prepared on behalf of the subcommission on Salt-Affected Soils of the ISSS. A final draft is to be prepared in the near future. Causes of salt accumulation in African soils were discussed and a bibliography of pertinent references was presented.

SELECTED BIBLIOGRAPHY

Published and unpublished reports on saline and sodic soils of Africa are so numerous that it is impossible to give an exhaustive list. The publications listed here are principally those utilizted in preparation of the latest map of salt affected soils. A large number of unpublished reports has also been used.

Belkhodja, K. 1972. Origine et caractéres de la salinité dans les sols de la plaine de Kairouan (Tunisie centrale), Sols de Tunisie, D.R.E.S. Tunis, 4, 105 p.

Bocquier, G. 1971. Génese et évolution de deux toposéquences de sols tropicaux du Tchad - O.R.S.T.O.M., Bondy, France, 351 p.

Brammer, H. 1971, 1973. Soils of Zambia, Division of Overseas Surveys, Tolworth, Surrey, England.

Brunt M. 1960. The land use map of Gambia, Division of Overseas Surveys, Tolworth, Surrey, England.

Cheverry, C. 1974. Contribution á l'étude pédologique des polders du Lac Tchad, O.R.S.T.O.M., Bondy, France, 280 p.

da Costa, J. Botelho. 1963. Soils of Angola, J.T.V., Lisbon, Portugal.

FAO-UNESCO (J. Ricquier), 1975. Carte des sols du monde, Afrique, 3 feuilles, UNESCO, Paris, France.

Jordan, H.D. 1964. The relation of vegetation and soil development of mangrove in Sierra Leone, J. Appl. Ecol. 1:209-212.

Hervieu, J. 1968. Contribution a l'étude de l'alluvionnement en milieu tropical: les facteurs de la sédimentation continentale; les produits de érosion, les sols alluviaux sur le versant occidental de Madagascar. Mémoire O.R.S.T.O.M., Bondy, France, n° 24, 465 p.

d'Hoore, J. 1964. La carte des sols d'Afrique, Commission de Collaboration Technique en Afrique, Lagos, 93, 210 p.

Maignien, R. 1965. Carte des sols du Niger (1/1,000,000), Cartes et Notices O.R.S.T.O.M., Bondy, France, n° 24.

Mitchell, A. 1967. A reconnaissance assessment of the irrigation potential of soils along the main rivers of Eastern Bechuanaland. Division of Overseas Surveys, Tolworth, Surrey, England.

Murdoch, G. 1970. Distribution of saline and alkali soils in some Africa countries. 2nd Approximation. M.R. 80, Division of Overseas Surveys, Tolworth, Surrey, England.

Northcote, K.H., and J.K.M. Skene. 1972. Australian soils with saline and sodic properties. C.S.I.R.O.S., Melbourne, Australia, Soil Publication No. 27, 62 p.

O.R.S.T.O.M. 1976. Carte pédologique des sols du Benin (1/200,000), O.R.S.T.O.M., Bondy, France.

Radwanski, S.A. 1969. Distribution of saline and alkali soils of some African countries, 1st Approximation, Division of Overseas Surveys, Tolworth, Surrey, England. M.R. 67, 100 p.

Riquier, J. 1967. Carte pédologique de Madagascar (1/1,000,000), O.R.S.T.O.M., Bondy, France.

Scott, R.M. 1961. Soil map of East Africa, East Africa Literature Bureau, Nairobi, Kenya.

Szabolcs, I. 1974. Salt affected soils in Europe, Research Institute for Soil Science and Agricultural Chemistry, **Budapest** , Hungary, 63 p.

Thompson, J. 1965. The soils of Rhodesia and their classification. Department of Research and Special Service, Salisbury, Rhodesia, Tech. Bull. 6.

Tomlinson, T.E. 1957. Changes in a sulphide containing mangrove soil. Emp. J. Exp. Agr. 25:108-118.

Vieillefon, J. 1974. Contribution a l'étude de la pédogénèse dans la domaine fluvio-marin en climat tropical d'Afrique de l'ouest. O.R.S.T.O.M., Bondy, France. 410 p.

SOIL DISTRIBUTION IN THE SOIL VOLUME
WETTED BY DRIP IRRIGATION WITH SALINE WATER IN AN ARID REGION

Mordechay Uzrad 1/

SUMMARY

The present work examined the zones of salt accumulation within the soil volume wetted by application of saline water through a drip irrigation system to a commercial vegetable field in an arid region. The composition of these salts was also determined.

Soil samples were taken from depths of 0-2, 5, 15, 30, and 45 cm. The following factors were determined: electrical conductivity (EC_{25}), chloride, sodium, potassium, calcium, and magnesium, and the exchangeable sodium percentage (ESP). After about 3 1/2 months of irrigation, the soil samples were collected within the area wetted by the emitters, as well as between the emitters and **between the drip laterals.**

When saline water is applied by drip irrigation, salt accumulation occurs at the periphery of the soil volume wetted by the emitters.

A low level of soil salinity was expected to be found immediately below the emitter, beyond a depth of 5 cm. The assumption is that because of the good leaching conditions in this zone, there will be a low salinity level similar to that of the water applied. This assumption was verified by the results of numerous field tests.

Results show that under actual field conditions in the Arava, the greatest accumulation of salts occurs in the upper region of the wetted volumes, in a surface soil layer whose thickness does not generally exceed 5 cm.

At the periphery of the wetted volume, below the surface 5 cm of soil, there are two characteristic zones:

1. Between the emitters: In all cases, this zone had a low salinity level after several months of irrigation, due to the overlapping of the wetted volumes of adjacent emitters.
2. Between the laterals: Here the regions of salt accumulation were not clearly defined, because of the nonuniform movement of water, as well as the varied distribution of the different salts over the wetted distance. The salinity level was medium at the periphery and at times even low when there was overlapping of the wetted volumes.

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Regarding the lower limits of the volume wetted by the emitter (the maximum depth sampled was 45 cm), there was a low level of salinity below the emitter at all depths. It is assumed that the salts were leached beyond the sampled depth.

For vegetable crops, there is no need to provide a leached layer greater than 45 cm, especially within the strip wetted by the drip lateral where the plant roots are concentrated. Samplings in the Arava have shown that vegetable roots (Solanaceae and Cucurbitaceae) are concentrated mainly in the upper 30 cm soil layer.

Determinations of the distribution of various salts within the wetted volume showed that sodium was transported a greater distance than calcium. As a result, at the periphery of the wetted zone on the soil surface there is a region with a high ESP. This ESP level causes dispersion of the clay particles with consequent disturbance of the soil structure and reduction in infiltration capacity. This in turn may reduce the efficiency of irrigation and leaching operations.

The upper soil layer in which salt accumulation occurs is relatively thin (<5 cm), and this is important for a number of reasons:

1. The salt concentration is so high that even in such a thin layer the accumulation is quantitatively significant.

2. The salts concentrated in this upper layer are part of the total salt content of the particular soil volume, so that as the accumulation in this layer increases, there will be less salt in the other regions.

3. The salinity of the upper layer is more critical than in any other part of the profile for germination and seedling establishment.

4. When leaching salts below the root zone by surface water application, salts in the upper layer must move through the entire profile.

In light of the above observations, it is suggested that after the end of an irrigation season in which saline water has been applied by dripping, the first tillage operation should be plowing to a depth of 30-40 cm. This will incorporate the upper soil layer to a depth which, at least during the beginning of the growing season, will be below the root zone of the vegetable crop.

At this depth, leaching of salts will take place because of two factors:

1. There is no significant upward movement of salts due to evaporation.

2. There is a downward flow of water (assuming the quantity of irrigation water applied is properly calculated), especially below the emitters. Thus, if it is necessary to supplement the leaching process, this can be accomplished by the drip system itself, at the beginning of the growing season, when the roots are still above the layer to be leached.

During the growing season there may also be overlapping of the wetted volumes between the emitters along the lateral, and between the laterals. Such leaching by dripping is indeed slow, but may be efficient, and there is no reason why it cannot be carried out over a period of weeks, until the roots reach this depth (if they do).

This technique of leaching may also improve the incorporated layer with its high ESP. All the sampling carried out showed that at a depth of 30-45 cm, the ESP level was low. The reason for this is the relatively high content of calcium and the low content of sodium, which apparently was leached to a greater depth.

Therefore, deep plowing will achieve two purposes:

1. Incorporation of the upper layer to a depth where processes of leaching and structure improvement occur.
2. Transfer to the soil surface of leached soil (from a depth where there is considerable biological activity) with a very low ESP.

Following such plowing, it will probably be possible to considerably reduce the quantity of water required for leaching of salts after a season of drip irrigation with saline water.

Occasionally, such leaching may not even be necessary after plowing. Supplementary leaching, if required, can be provided at the same time that irrigations are given for field preparation, and also by drip irrigation during the early stages of the growing season.

INVESTIGATIONS INTO USE OF HIGHLY SALINE WATERS IN AN ARID ENVIRONMENT

I. SALINITY AND ALKALI HAZARD CONDITIONS IN SOIL UNDER A CYCLIC MANAGEMENT SYSTEM

R. D. Dhir [1]

SUMMARY

The occurrence of saline ground waters is common in western Rajasthan. An analysis of 3275 samples from western Rajasthan showed that 37.6, 26.4, 20.1, 9.0, and 7.0 percent of the samples fell in the salinity ranges of less than 2.2, 2.2-5, 5-10, 10-15, and over 15 mmhos/cm EC, respectively. Sodium chloride is by far the dominant salt, and SAR values were between 15 and 40 for 80 percent of the waters. Magnesium generally exceeds calcium, with both present as bicarbonate in low salinity water and as chloride and sulfate in high salinity water. Residual sodium carbonate generally is absent.

Because of the scarcity of fresh waters, groundwaters often are the main source of water for irrigation, and presently 0.29 million hectares are under irrigation from groundwater sources in the arid part of Rajasthan. There is a large average in the neighboring states of Haryana, Uttar Pradesh, and Gujarat. In 1969, the Central Arid Zone Research Institute undertook a five year monitoring study of soil and irrigation water salinity, alkali hazard, crop growth, and soil management on thirty-five farms where saline groundwater had been in regular use from less than ten years to more than 50 years.

In the study area of the northwestern part of Pali-District, the mean annual rainfall is 415 mm, received almost entirely during the summer monsoon months. Irrigation is from dug wells and a salt resistant wheat called Kharchia and, sometimes, barley are the crops. In 29 cases, wheat is grown from November to March, after which the land lies fallow through the next two rainy seasons (about 19 months). In six cases, wheat is **grown** during the winter every year; the land is fallowed during the summers. On the 29 farms, **individual holdings are divided into two** parcels which receive irrigation in alternate years so that the wells are not idle.

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Results showed that at the start of the irrigation season, the entire profile of soils having a loam or coarser texture and the upper 40 cm of finer textured soils had EC values of the saturation extract of between 1.2 and 2.5 mmhos/cm. At the close of the season, the soils showed a huge increase in salinity. An irrigation water salinity of 5 to 17 mmhos led to a soil salinity - after one growing season - of 4.5 to 13 mmhos.

Leaching during the rainy season removed much or all of the salts accumulated during the growing season. In years such as 1971 and 1972 when 59 and 63% of normal rainfall was received, complete leaching of accumulated salts was achieved in just one rainy season on loamy sand sites.

The alkali hazard of the irrigation water was sufficiently high to lead to concern about exchangeable sodium accumulation in the irrigated soils. However, the data show that sandy loam to gravelly loam sites showed 80% leaching in the 0-40 cm depth. In finer textured soils, one year of rainfall desalinized this depth to the extent of 50 to 80% only. During 1970, which had 142% of average rainfall, complete leaching of accumulated salts was seen in this depth in all soils except the finest textured. An exceptionally wet year like 1973 (893 mm) alone, was enough for complete leaching of all the salts from soils of all textures. The second year of fallow led to progressive desalinization and was particularly effective in years when the preceding rainy season of the fallow period had been below average. The rain during two consecutive drought years, as happened in 1971 and 1972, was enough to desalinize 0-40 cm of even the finest textured soils. The foregoing results show that accumulated salinity is taken care of by one above-average years' rainfall or two subnormal rainy seasons. Some salinity is still retained in the 40-60 cm depth, particularly in clay loam and finer soils, in most years, but this has not been found to interfere to any appreciable extent. Rain of above average years like 1973 is able to take care even of such residual salinity.

Values of exchangeable sodium in the 0-20 cm soil depth in all except one case are much lower, and in 20-40 cm depth equal or slightly higher, than what would be predicted if the soils were in equilibrium with the irrigation water. It is clear that saline water has not only resulted in no progressive build up of the alkali hazard after prolonged use but also that the values in fact are even lower than what could be predicted from the SAR of the irrigation water.

INVESTIGATIONS INTO USE OF HIGHLY SALINE WATERS IN AN ARID ENVIRONMENT

II. GROWTH OF CROPS UNDER HIGH SALINE WATER IRRIGATION.

R. D. Dhir and B. L. Jain [1]

SUMMARY

Results of a comparative study of two wheat varieties and of long term observations on crop growth in cultivators' fields under highly saline water irrigation in a cycle (wheat fallow) management system are reported. In saline water use, the variety kharchia-65 performs better than a high yielding Indian selection from Mexican Sonora 64, (Kalyan Sona). The contributing factor is primarily the greater number of tiller. Grain quality is good and nutrient uptake is not seen to be interfered with in highly saline-sodic conditions. Observations on growth in cultivators' fields show that with waters between 5 to 10 mmhos E.C. and soil salinity at harvest time less than 11.5 mmhos E.C$_e$, yields of over 16 quintals (q)/ha are generally obtained. With irrigation water of higher salinity but soil salinity still below the critical salinity mentioned above, yields are 10 to 15 q/ha. When waters have naturally occurring nitrates, particularly above one m.e/l, yields are even better. Results obtained conclusively show that even highly saline-sodic waters are usable if the land is fallowed during the rainy season. These waters offer good scope for use in augmenting and stabilizing production in an arid environment.

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EFFECT OF PRESOWING-HARDENING AND GRADUAL EXPOSURE TO NaCl ON GROWTH, CELL-SAP OSMOTIC PRESSURE AND pH OF TOMATO AND BARLEY PLANTS

M.N. El-Shourbagy and A.M. Ahmed [1]

SUMMARY

Seeds of tomato (Lycopersicum esculentum L. var. Pritchard) and seeds of barley (Hordeum vulgare L. var. Sahrawi) were germinated in sand in a glasshouse. Two weeks after sowing for barley was four weeks for tomato, seedlings of similar growth dimensions were transferred to cylindrical glazed pots of 41 capacity containing a Hoagland nutrient solution. The pH was maintained at 6.5. The solution was continously aerated, replaced with a fresh one every two weeks, and the volume maintained constant during the experiment.

In the presowing salt-hardening experiments, dry seeds were divided into 3 lots; one soaked in distilled water, another in 1 M NaCl solution, and the third was kept dry. After 24 hours seeds were planted in sand until seedlings attained the appropriate height, then transferred to solution cultures containing the base non-saline nutrient solution. After one week, seedlings were transferred to NaCl levels in solution culture. The NaCl concentrations used were 0, 0.05, 0.1, 0.15, and 0.2 M, having OP of 0.36, 3.62, 5.14, 8.20, and 10.06 atm respectively. Saline solutions were prepared by dissolving the appropriate amounts of NaCl in the base nutrient solution to give the required Molar concentration of NaCl.

In the gradual exposure to NaCl increments seedlings cultured in the base non-saline nutrient solution for one week were exposed to graded levels of NaCl in the solution culture at regualr periods of one week each for each level. One week from the transfer of seedlings to the base non-saline solution, most of the plants were transferred to another solution containing 0.05 M NaCl; one group of plants remained in the base non-saline solution until the end of the experiment. After another week, most of the plants, again, were transferred from the culture solution salinized with 0.05 M NaCl to another one salinized with 0.1 M NaCl; one group of plants remained in the 0.05 M NaCl solution until the end of the experiment. The same precedure was followed until the 0.2 M NaCl concentration was reached. This took 5 weeks from the beginning of the experiment. Plants of each pot were separated into shoots and roots for fresh and dry weight determinations. Osmotic pressure was measured cryoscopically on the expressed cell-saps of shoot and root and their pH values.

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The presowing water-soaking of seeds stimulated the fresh and dry weights of tomato at the highest NaCl level (0.2 M), but inhibited those of barley shoots, while presowing salt-hardening increased salt tolerance in barley more than in tomato. With exposure to graded NaCl increments the two plant species adjusted to increased NaCl concentrations in the culture media at all levels. Both species exposed to graded NaCl increments attained greater fresh and dry weights than those grown continuously under the corresponding fixed NaCl levels. Tomato showed much better growth when the graded 0.2 M NaCl level was reached. The fresh and dry weights were about 3 times greater than those grown under non-graded salinity conditions. Both species tended to achieve a more balanced shoot cell-sap pH compared with those exposed continuously to a fixed NaCl level. With gradual exposure to NaCl increments, fresh and dry weight-stimulation coincided with increased internal osmotic pressure in both species, which was accompanied with greater Na and Cl contents in tomato, but not in barley. This might suggest the existence of two different mechanisms for salt adjustment.

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